Passive Acoustic Monitoring Study

Hilcorp's 2015 Geohazard Survey in Foggy Island Bay, AK

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Executive Summary

Acoustic monitoring was conducted with two underwater, autonomous, acoustic recorders between 6 Jul and 22 Sep, 2015 in Foggy Island Bay, AK. The monitoring occurred before, during and after a shallow geohazard and ice gouge survey conducted by Hilcorp Alaska, LLC at their Liberty prospect. Hilcorp's survey employed a total of two vessels and sonar sources including single beam, multi-beam, and side scan sonars and sub-bottom profilers. The sub-bottom profilers were the only sources that operated at frequencies audible to marine mammals. The survey occurred over one week, between 12 and 19 Jul and the sub-bottom profilers were active on 5 days, for a total of 14 hours during the survey.

The goals of the acoustic monitoring program were not to provide detailed sound source characterization of the survey sources, rather to provide an acoustic characterization of the environment surrounding the survey, including quantifying marine mammal occurrence, both during and after the survey. The acoustic recorders were located at a minimum distance of 500 m from the survey activities, at 0.5 and 5 km range offshore from the proposed Liberty Island location.

Detected marine mammal vocalizations included those from belugas and pinnipeds. Belugas were only detected on five days and pinnipeds were detected more frequently (10 days on the nearshore recorder and 66 days further from shore). Bearded seal vocalizations were detected on two days, with unidentified pinnipeds comprising the remaining detections. The numbers of marine mammal vocalization detections is consistent with the expected presence of marine mammals indicated by past visual observations and tagging studies in the project area.

The median, broadband ambient sound levels recorded during the monitoring program were 96 and 98 dB re 1 µPa nearshore and further from shore, respectively. Statistical distribution of the ambient sound levels with frequency generally followed the expected trends for weather-driven ambient sound conditions with occasional influence from vessel noise. The levels were consistent with past data collected at nearby locations. Average sound levels recorded on the AMARs during Hilcorp's survey were no louder than those recorded after the survey completed. Vessel noise and noise from the sub-bottom profiler were detectable during the survey. However, at the measurement locations (i.e. at ranges greater than 500 m from the survey activities) these sources did not result in statistically notable sound level excursions in excess of the measured variability of local non-survey sound levels due to weather events or unrelated vessel noise. Noise from the survey vessels and sub-bottom profilers did not appreciably alter the local soundscape measured at ranges greater than 500 m from the survey activities.

1. Introduction

Hilcorp Alaska, LLC (Hilcorp) conducted a shallow geohazard and strudel scour survey (the “survey”) with a transition zone component in United States (U.S.) federal and state waters of the Beaufort Sea during the 2015 open water season. Survey data was acquired from 12 through 19 July. This survey was conducted in support of the development of the Liberty field located in Foggy Island Bay.

The survey required two vessels and the use of underwater sonar sources that emitted high-frequency sound into the water. Although underwater sound sources can potentially cause behavioral disturbance or auditory injury (permanent or temporary) to marine mammals, existing measurements of underwater noise from sources similar to those used in the survey indicated that the potential for such impacts was limited to areas very near to the sources (within 50 m range). Hilcorp obtained authorizations from the National Marine Fisheries Service (NMFS), the U.S. Fish and Wildlife Service and the North Slope Borough to conduct the survey, subject to implementation of mitigation measures that prevented acoustic impacts at ranges close to the sources. Because the region of potential impact was relatively small and potential impacts were mitigatable, the authorizing agencies did not require that Hilcorp conduct a sound source characterization of the survey sources. Instead, an acoustic monitoring program was designed to address knowledge gaps about ambient sound levels around the survey area and the presence, distribution, and migration paths of marine mammal species occurring near the Liberty field. This report provides results from that acoustic monitoring program.

Three months of autonomous passive acoustic data were collected using two Autonomous Multichannel Acoustic Recorders (AMARs, JASCO Applied Sciences) that were deployed from 6 Jul to 22 Sep. The AMARs recorded acoustic data from distances greater than 500 m from the survey activities, at 0.5 and 5 km range offshore from the proposed Liberty Island location. The acoustic data were processed to characterize the ambient sound levels and the presence of marine mammals including bowheads, belugas, and seals. Long-range propagation of sounds from the survey was assessed through examination of the sound levels received during the survey relative to the ambient noise data collected outside of the survey times.

1.1. Background

The Liberty reservoir is located in U.S. federal waters in Foggy Island Bay about 8 miles (mi) east of the Endicott Satellite Drilling Island (SDI). The depth and distribution of ice gouges into the seabed and the existence and location of archaeological resources (site clearance) were investigated with strudel scour and shallow hazard surveys focused on the upper 1,000 m (3,280 ft) of the seabed within select areas of interest near offshore drilling locations and proposed pipeline corridors.

Various types of equipment were used in the survey: single-beam and multi-beam echosounders, side-scan sonar, high and low resolution sub-bottom profilers, and a magnetometer. Sonar equipment emitted very high to low frequency continuous acoustic sounds on limited areas of the ocean bottom and intermediate water column. The operating frequencies of the multi-beam, single-beam, and side-scan sonar equipment were outside the functional hearing ranges of all marine mammals (Table 1, Southall et al. 2007). Sound generated by the sub-bottom profilers, however, was within the hearing range of all marine mammal species found in the project area (Southall et al. 2007). Measurements of a similar sub-bottom profiler, collected at a deeper water location compared to this survey (36 m water depth), yielded sound pressure levels of 160, 180, and 190 dB re 1 μPa to a distance and depth of 30 m (100 ft) from the source (Warner and McCrodan 2011).

Table 1 Client provided specifications for sonar sources used during the survey.

Sound Source	Operating Frequency (kHz)	Horizontal beamwidth (degrees)	Vertical beamwidth (degrees)	RMS Source level (dB re 1 µPa @ 1m)	Maximum pulse rate (Hz)
Edgetech 3200 high-resolution (CHIRP) sub-bottom profiler	2–24	15–24	15–24	210	3–10
Applied Acoustics AA251 low-resolution sub-bottom profiler	1–4	N/A	N/A	212	7
Odom single-beam echosounder	210	3	3	220	20
Norbit iWBMS multi-beam echosounder	400	1.9	0.9	218	40
Edgetech 4125 side scan sonar	400 / 900	0.5	50	215	75

Hilcorp was permitted to conduct the survey within a 6.5 km^2 (2.5 mi^2) area, which included 483 km (300 mi) of planned survey lines. The specific area surveyed was the proposed Liberty Island pipeline route, a 600 m (1,969 ft) wide corridor located 17 km (11 mi) southeast of Endicott and extending from the proposed Liberty Island locationto shore. Water depths in the survey area ranged from 1 to 13 m (3 to 42 ft). The project vessel started sonar testing on 9 July; survey data acquisition occurred from 12 through 19 July. The survey vessel covered 729 km (452 mi), the vessel tracks are shown in Figure 1 (from Cate et al. 2015), whichalso shows the survey project area, between 70°12.0′N and 70°17.0′N and between 147°32.0′W and 147°46.0′W. The vessel tracks in the figure includes lines for activities conducted outside of the project area, such as vessel transit, and other vessel movements for project support and logistics

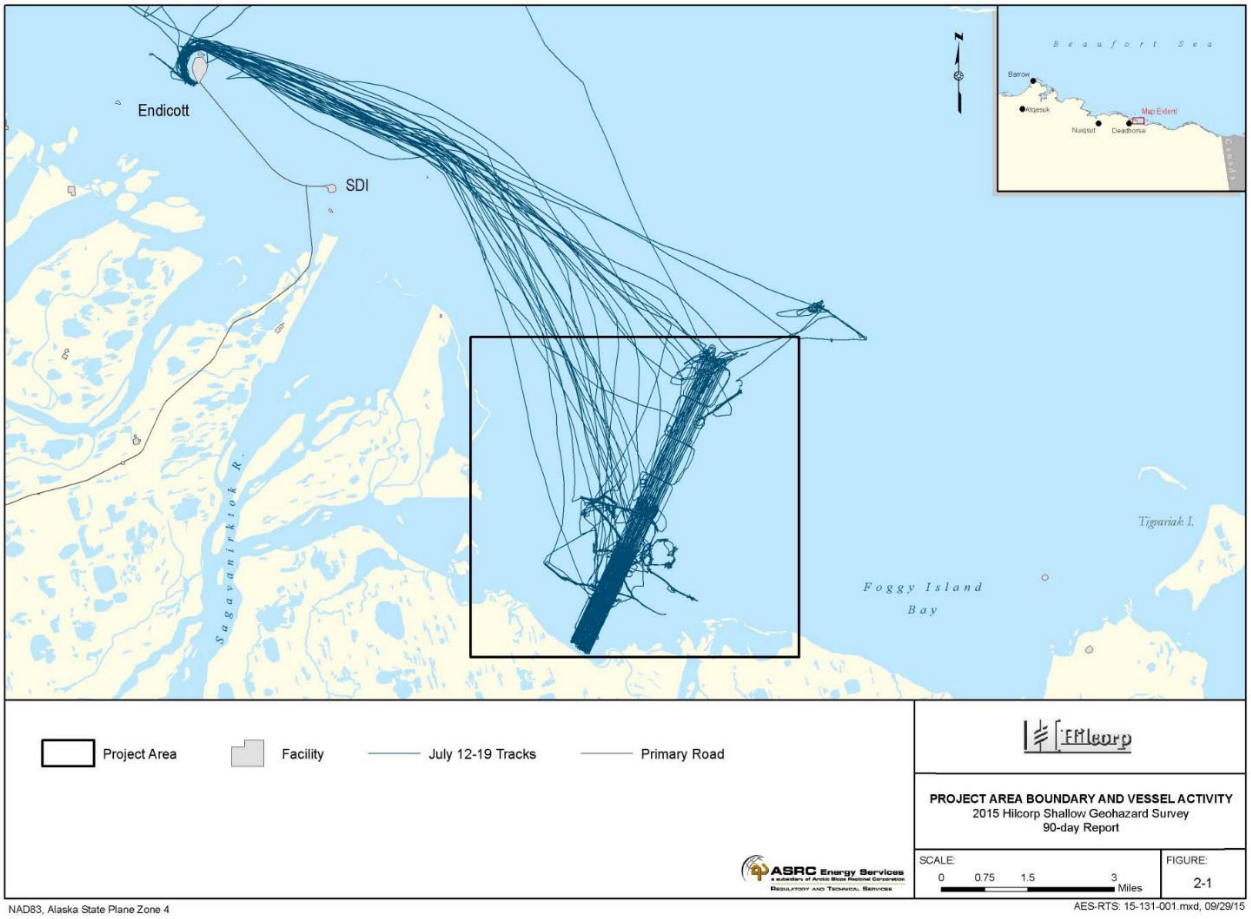

Figure 1. Project Area Boundary and vessel activity (Cate et al. 2015).

1.2. Acoustic Monitoring Study

In conjunction with the survey, passive acoustic monitoring data were collected by JASCO Applied Sciences (Alaska), Inc. (JASCO). This acoustic monitoring was conducted to fulfill NMFS requirements for collecting data to assist with assessing effects from industry on the marine environment and the availability of local subsistence resources. The goals of the acoustic monitoring were to document ambient noise conditions, to characterize the long-range propagation of sounds produced during the survey, and to examine the spatial and temporal distribution of marine mammals based on acoustic detections of their vocalizations. JASCO used two AMARs to measure underwater sounds; the AMARs were in place before the survey began and retrieved at the end of the open water season.

Current knowledge on marine mammal presence and distribution in this area is largely derived from visual surveys. This acoustic monitoring study augments the visual survey data to help address knowledge gaps about spatial and temporal distributions, habitat use, calling behavior, and migration paths of several marine mammal species in this area.

1.3. Marine Mammal Activity in the Project Area

The most common marine mammal species located in the Beaufort Sea are the bowhead whale (*Balaena mysticetus*), gray whale (*Eschrichtius robustus*), beluga whale (*Delphinapterus leucas*), bearded seal (*Erignathus barbatus*), ringed seal (*Phoca hispida*), spotted seal (*Phoca largha*) and Pacific walrus

(*Odobenus rosmarus divergens*). Polar bears (*Ursus maritimus*) are also present in the area but due to their limited reliance on underwater communication, they are not considered in this underwater noise report.

1.3.1. Bowhead whales

Bowhead whales are circumpolar, ranging throughout high latitudes in the Northern Hemisphere. The Western Arctic stock is the largest of four bowhead stocks recognized worldwide by the International Whaling Commission (IWC 2010, Allen and Angliss 2015) and is found throughout the Bering, Chukchi, and Beaufort seas.

The Western Arctic stock migrates annually from wintering areas (December to March) in the Bering Sea, through the Chukchi Sea in the spring following open ice leads (April through May). The stock then feeds in the Canadian Beaufort Sea where they spend much of the summer (June through early to mid-October) before returning again to the Bering Sea in the fall (September through December) to overwinter (Braham et al. 1980, Braham et al. 1984, Moore and Reeves 1993, Rugh et al. 2003, Quakenbush et al. 2010, Allen and Angliss 2015). Citta et al. (2015) reported that most of Bering-Chuchki-Beaufort Seas bowhead whales (tagged animals) migrate past Point Barrow, toward Cape Bathurst, in spring. Between mid-July to late September most tagged whales are located in shallow shelf waters adjacent to the Tuktoyaktuk Peninsula. The project area is not identified as a core-use area (area of concentrated use) for this species (Citta et al. 2015). The Bering-Chukchi-Beaufort Seas bowhead whale population was estimated at 16,892 in 2011 (Givens et al. 2013).

1.3.2. Gray whales

Most whales in the eastern North Pacific population feed from late May to early October in the Chukchi, Beaufort, and northwestern Bering Seas (Rice and Wolman 1971, Nerini 1984, Rice 1998, Moore et al. 2003) then move to their breeding and calving areas in Baja California and Mexico (Rice and Wolman 1971, Rice et al. 1981, Allen and Angliss 2015). Typically, gray whales inhabit shallow water, remaining closer to shore than any other large cetacean throughout the year. Thus, they are considered common summer residents in the nearshore waters of the Beaufort Sea. The most recent population estimate from abundance counts in 2006/2007 was approximately 19,000 whales (Laake et al. 2012).

1.3.3. Beluga whales

Of the five beluga stocks present in Alaska (O'Corry-Crowe et al. 1997, Allen and Angliss 2015), the Beaufort Sea and Eastern Chukchi Sea stocks have been documented within the project area boundary. Both stocks are thought to overlap in the Beaufort Sea, though most individuals observed during the project are likely from the Beaufort Sea stock.

The general distribution pattern for beluga whales shows major seasonal changes. During the winter, they occur in offshore waters associated with pack ice. Both stocks winter in the Bering Sea (Suydam et al. 2001, Allen and Angliss 2015). In the spring, Beaufort Sea stock migrate to warmer coastal estuaries, bays, and rivers where they molt and give birth to and care for their calves (Allen and Angliss 2015). Suydam et al. (2001) reported that during summer, tagged Eastern Chukchi beluga whales moved to deep offshore waters (about 3,000 m) with heavy ice cover (more than 90%).

1.3.4. Ringed seals

Ringed seals have a circumpolar distribution; the subspecies *Phoca hispida hispida* is present in the Arctic Ocean and Bering Sea. Ringed seals tend to prefer large ice floes and often inhabit interior pack ice where sea ice covers over 90 percent of the water (Simpkins et al. 2003, Kelly et al. 2010b). Ringed seals are year-round residents in the Beaufort, Chukchi, and Bering Seas and move seasonally coinciding with ice melting and retreating (Burns 1970, Frost and Lowry 1984, Frost 1985, Freitas et al.

2008, Kelly et al. 2010b, Crawford et al. 2012, Harwood et al. 2012b). Studies using satellite tracked animals have revealed seasonal differences in habitat use strategies (Crawford et al. 2012), notably relatively restricted movements in winter and early spring (Kelly et al. 2010a) and extensive migrations during fall and winter (Harwood et al. 2012a).

1.3.5. Spotted seals

Spotted seals are distributed along the continental shelf of the Bering, Chukchi, and Beaufort Seas, and the Sea of Okhotsk south to the western Sea of Japan and northern Yellow Sea. Spotted seals that inhabit the Beaufort Sea belong to the Bering Distinct Population Segment (Allen and Angliss 2015). Spotted seals are coastal pinnipeds that summer in nearshore areas in the Beaufort, Bering, and Chukchi Seas and winter along the ice edge in the Bering Sea (Quakenbush 1988, Lowry et al. 1998, Simpkins et al. 2003). A satellite-tagged spotted seal moved from Kasegaluk Lagoon to Smith Bay and back between August and September (Lowry et al. 1998).

1.3.6. Bearded seals

Bearded seals have a circumpolar distribution throughout the Arctic. The Beringia population occurs in the northern Bering, Chukchi, and Beaufort Seas (Mansfield 1967). Bearded seals winter in the Bering Sea along the ice front, but then move north in the spring with the receding ice edge (Burns 1981, Allen and Angliss 2015). During summer, populations are present in both the Chukchi and Beaufort Seas in high ice coverage areas along the pack ice edge (Burns 1981, Simpkins et al. 2003, Bengston et al. 2005, Laidre et al. 2008, Allen and Angliss 2015). In the Beaufort Sea, bearded seals were vocally present year-round (MacIntyre et al. 2013).

1.3.7. Walrus

Pacific walrus migrate between the Chukchi and Bering Seas with the seasonal melting and accretion of sea ice each year (Jay et al. 2012). After wintering in the Bering Sea (Jay and Hills 2005), walruses move to Chukchi Sea in May with the formation of open leads in sea ice north of the Bering Strait and a major ice flaw along the northwestern coast of Alaska (Fay 1982). During summer, walruses continued to move northward into the eastern Chukchi Sea and in the western Chukchi Sea (Fay 1982). In fall, starting in October, walruses migrated southward and by November, most of the population occurred south of the Bering Strait. Although unusual in the Liberty project area, occasional takes of walrus have been reported by Cross Island hunters and walruses have been observed beaching at the Endicott and Northstar facilities (B. Streever, 2016 pers. comm.).

Table 2. Known marine mammal species in the project area: their occurrence and the characteristics of the main underwater sounds they produce. Status assessment by the Marine Mammal Protection Act (MMPA), Endangered Species Act (ESA), and Federal Register (FR).

Species	Main period of residency in the Beaufort Sea	Dominant vocalization frequency range	Reference	MMPA	ESA	FR
Baleen whales						
Bowhead whale	June to October	100–400 Hz (moans)	Clark and Johnson (1984)	Protected	Endangered	Endangered (35 FR 18319)
Gray whale	late May to early October	< 1 kHz (moans, pulses and bonging sounds)	Crane and Lashkari (1996), Stafford et al. (2007b)	Protected		
Beluga whale	Spring/Summer	> 1 kHz (Whistles and pulsed/noisy calls)	Chmelnitsky and Ferguson (2012)	Protected		
Pinnipeds						
Ringed seal	Year-round	10–1500 Hz	Stirling (1973), Jones et al. (2014)	Protected	Threatened	Threatened (77 FR 76705)
Spotted seal	Summer	Not well characterized		Protected		
Bearded seal	Summer	10–11000 Hz	Risch et al. (2007), Frouin-Mouy et al. (2015)	Protected		
Walrus	Summer (rare)	10-20000 Hz	(Schusterman and Reichmuth 2008)		Candidate for listing	

2. Methods

Underwater sound was recorded at two stations for nearly three months from 6 Jul to 22 Sep 2015. JASCO′s automated marine mammal detection and classification algorithms were applied to the data to quantify marine mammal vocalizations. Automated analysis also quantified ambient noise levels and statistics for sounds recorded on each AMAR.

2.1. Acoustic Data Acquisition

Acoustic data were acquired using two Autonomous Multi-Channel Acoustic Recorders (AMARs, JASCO Applied Sciences). Twenty-four bit samples were recorded on 1.8 TB of internal solid-state memory. Each AMAR (Figure 2) was fitted with an HTI-99-HF omnidirectional hydrophone (High Tech, Inc.; −164 dB re 1 V/µPa nominal sensitivity). AMAR 1 sampled at 64 ksps (10 Hz to 32 kHz acoustic recording bandwidth) continuously. AMAR 2 recorded in consecutive 30-minute cycles where 24-bit samples were recorded at 64 ksps for the first 28 minutes and then 16-bit samples were recorded at 375 ksps for the last 2 minutes. The higher sample rate data from AMAR 2 provided an acoustic recording bandwidth of 10 to 187.5 kHz; these data were analyzed for high-frequency beluga whale clicks and whistles that would not be detectable in data recorded at the lower sample rate. This duty cycle was chosen to optimize the recording duration given the available memory capacity of the recorder. The high-frequency duty cycle configuration was not implemented on AMAR 1 such that it would record a complete record of uninterrupted, high-resolution (24-bit) acoustic data.

Figure 2. Left: Autonomous Multichannel Acoustic Recorder (AMAR; JASCO Applied Sciences). Right: Assembled AMAR just prior to deployment with frame, hydrophone shroud, ground line and anchor.

The recorders were deployed near the Liberty prospect and were aligned with the survey line, at nominal distances of 500 and 5000 m from the offshore end of the survey line for AMARs 1 and 2, respectively (Figure 3 and Table 3). The recorders were inside the barrier islands, an area where we do not expect there to be many bowhead or beluga whale detections. Each AMAR was moored on the seafloor under its own weight and was housed in a frame to elevate the hydrophone above the sediment (Figure 2). Each frame was connected to a ground line used to retrieve equipment by grappling (Figure 5).

Each mooring was comprised of:

- An AMAR with square frame
- 100 m sinking ground line
- A 10 lb anchor weight

All mooring components were acoustically isolated to minimize noise induced by the mooring. The hydrophone was placed in a cage covered by a shroud to minimize flow noise.

Table 3. Deployment and retrieval dates and deployment locations of the acoustic recorders. AMARs 1 and 2 were still recording upon retrieval.

Station	Latitude	Longitude	Depth (m)	Deployed	Retrieved
AMAR 1	70° 16.739' N	147° 34.757' W	7.0	6 Jul 2015	22 Sep 2015
AMAR 2	70° 18.870' N	147° 31.595' W	7.2	6 Jul 2015	22 Sep 2015

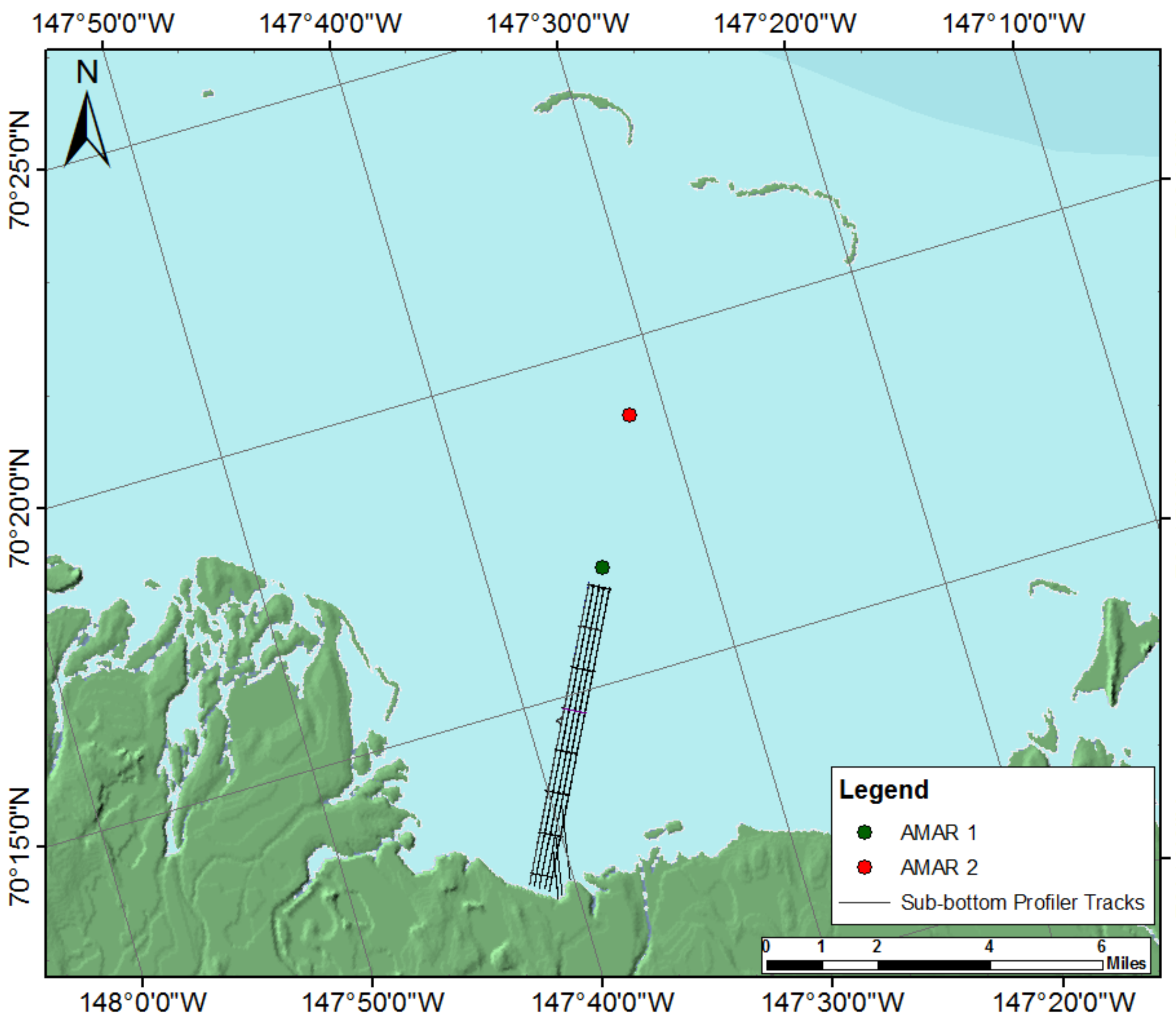

Figure 3. Acoustic monitoring area and AMAR locations relative to tracks along which the sub-bottom profiler was active.

Figure 4. M/V *Journey* was used to deploy and retrieve AMARs (www.hdradvantage.com).

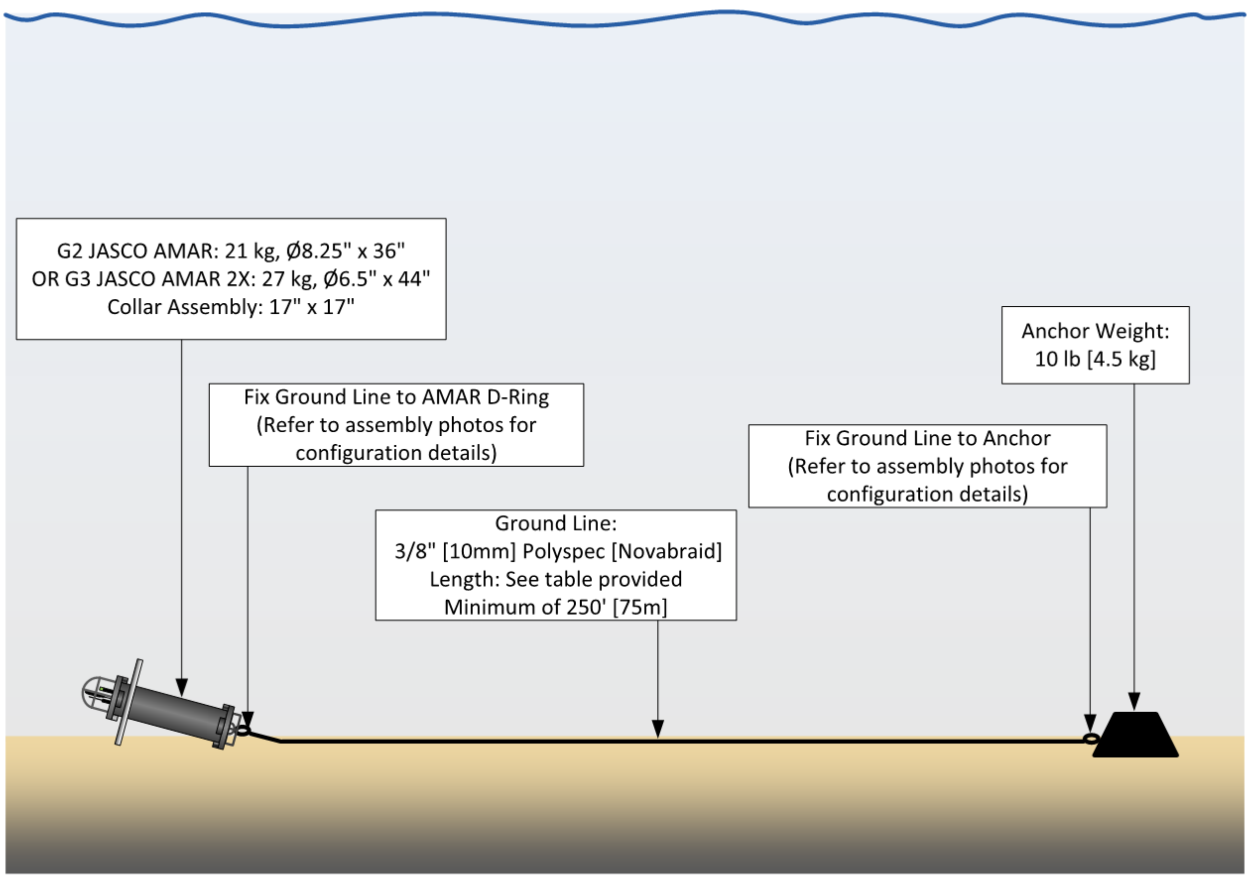

Figure 5. Autonomous Multichannel Acoustic Recorder (AMAR) with frame, ground line, and anchor. This design allows the AMAR to be retrieved by grappling.

2.2. Data Analysis

Acoustic data were analyzed using a combination of automated and manual techniques. Ocean sound levels and the proportion to which anthropogenic activities contributed to them were quantified using automated procedures (Section 2.2.2). Statistics (Appendix A.3) were computed to characterize the ocean noise when the survey occurred and when no survey activities took place.

Marine mammal calls were detected and classified both manually and with JASCO's automated acoustic analysis software suite (Sections 2.2.1 and 2.2.2, respectively). Aside from establishing the acoustic occurrence of animals, manual analysis was performed to identify call types and to verify that the automated detector did not miss the presence of vocalizing target species. Because of their conservation status and their importance to the Beaufort Sea communities, both manual and specialized automated approaches were used for bowhead and beluga whale. A walrus grunt detector/classifier was used to evaluate the vocal presence of this species. Bearded seal calls were detected with a generic automated detector and by manually analyzing the calls. Calls of other species were detected by manually analyzing 5% of the recorded data.

2.2.1. Manual data analysis

Marine mammal call detections were analyzed using JASCO's SpectroPlotter, customized software that standardizes annotations and approaches among analysts. Three trained analysts visually examined spectrograms in SpectroPlotter and, when needed, by simultaneously listening to audio playbacks. Two analysts had several years of experience classifying Arctic marine mammal vocalizations in previous Chukchi Sea and Bering Sea datasets.

The purpose of the manual analysis was to:

- Verify that automated classifiers did not miss target species (bowhead, gray whale, beluga whale, bearded seal and walrus).
- Assess the vocal presence of target species for which we do not have an automated detector (ringed seal and spotted seal) in the Liberty project area.
- Identify non-target and extralimital species.

Five percent of the 64 ksps data were reviewed manually for presence of marine mammal calls, which translates to reviewing 90 s of data every 30 min. The analysts annotated one call per species in each 90 s sample.

JASCO's lead analyst reviewed a random subset of annotations from both deployments to ensure calls were accurately classified. The lead analyst resolved, when possible, the species identity for unidentified annotated calls. The annotation review entailed verifying a sample of annotations of target (bowhead, gray, and beluga whales, and ringed, spotted, and bearded seals) and non-target species, specifically focusing on annotations of less common species or those outside the expected range or residency period of common species, and identifying species tagged as "Unknown" by reviewing sample sounds. Unknown sounds for which analysts indicated a possible source were prioritized, especially if the source could be one of the targmet species and had not yet been detected on that date.

2.2.2. Automated data analysis

To accurately analyze the 2.8 TB of acoustic data collected during the summer, we used a specialized computing platform operating approximately 700 times faster than the recording duration (i.e., 700 h of recorded data could be analyzed in 1 h of computation time). The system allows automated analysis of total ocean noise, seismic survey sounds, vessel noise, and possible marine mammal calls. Figure 6 shows a block diagram outlining the stages of the automated analysis. Bowhead and beluga whale calls were detected and classified with algorithms coded in MATLAB programming software (Mathworks Inc.)

and executed separately on the computing platform. Appendix B contains details about each of the automated processing steps.

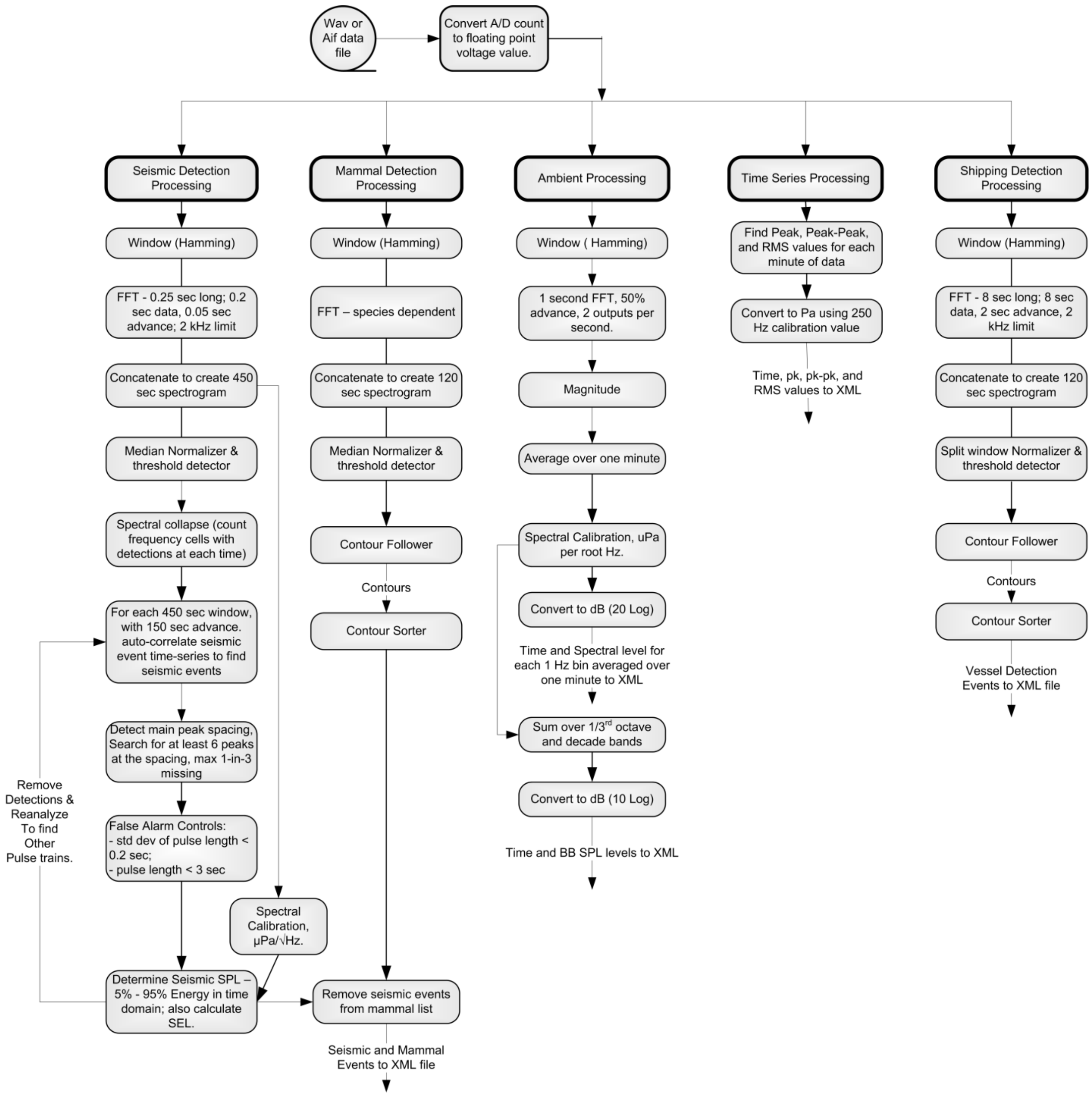

Figure 6. Major stages of JASCO's automated acoustic analysis software suite.

2.3. Ambient noise descriptors

Ambient noise levels at each recording station are presented as:

- Broadband and approximate-decade band sound pressure levels (SPLs) over time for these frequency bands: 10 Hz to 32 kHz, 10–100 Hz, 100 Hz to 1 kHz, and 1–10 kHz, 10–32 kHz. See Appendix A for a description of these metrics.

- Spectrograms: Ambient noise at each station was analyzed by Hamming-windowed fast Fourier transforms (FFTs), with 1 Hz resolution and 50% window overlap. The 120 FFTs performed with these settings are averaged to yield 1 min average spectra.
- Statistical distribution of sound pressure levels in each 1/3-octave band. The boxes of the statistical distributions indicate the first (25%, L_{25}), second (50%,L_{50}), and third (75%, L_{75}) quartiles. The whiskers indicate the maximum and minimum range of the data. The x indicates the root-mean-square (rms) in each 1/3-octave. See Appendix A for a description of these acoustic metrics.
- Spectral level percentiles: Histograms of each frequency bin per 1 min of data. The 5th, 25th, 50th, 75th, and 95th percentiles are plotted (L_5 ,$L_{25,}$ L_{50}, $L_{75,}$ $L_{90)}$. The 95th percentile curve is the frequency-dependent level exceeded by 5% of the 1 min averages. Equivalently, 95% of the 1 min spectral levels are below the 95th percentile curve. (see Appendix A.3). The 50th percentile (median of 1 min spectral averages) can be compared to the well-known Wenz ambient noise curves (Appendix A.2), which show ranges of variability of ambient spectral levels as a function of frequency of measurements off the US Pacific coast over a range of weather, vessel traffic, and geologic conditions. The Wenz curve levels are generalized and are used for approximate comparisons only. The 1 min averaged, 1 Hz spectral density levels are summed over the 1/3-octave and decade bands to obtain 1 min averaged broadband levels (dB re 1 µPa).
- Daily cumulative sound exposure levels (SEL (24 h)), which is the linear sum of the 1 min sound exposure levels (SELs).

3. Results

3.1. Manual and Automated Marine Mammal Vocalization and Click Detections

The manual analysis and automated data analysis yielded vocalizations of beluga whales, bearded seals, and unidentified species of pinnipeds. Bowhead whales, gray whales, walruses and ringed seals were not detected acoustically in the Liberty project area during the recording period.

3.1.1. Odontocetes

3.1.1.1. *Beluga whale*

The only manually and automated detected odontocete species was beluga whale. Beluga calls were detected on 5 days at AMAR 1 (14 Jul, and 3, 4, 8, and 13 Aug) and 4 days at AMAR 2 (3, 4, 9, and 13 Aug); plotted in Figure 7.

The detected beluga calls included a variety of whistles, buzzes, clicks and other high-frequency calls previously described for that species (Figure 9; Karlsen et al. 2002, Belikov and Bel'kovich 2006, Belikov and Bel'kovich 2008). Figure 8 shows an example of beluga calls detected on AMAR 1.

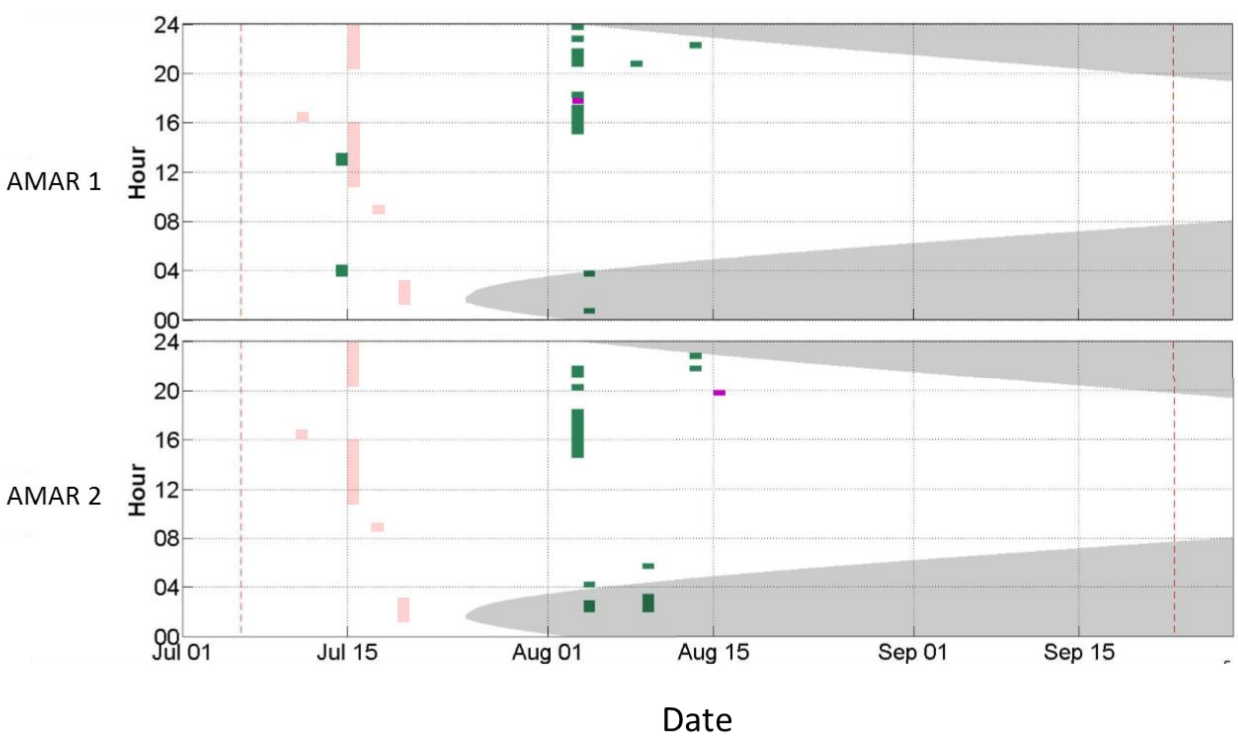

Figure 7. Daily and hourly occurrence of beluga whale (green) and bearded seal (purple) calls recorded at AMARs 1 and 2 from 6 Jul to 22 Sep 2015. Shaded areas indicate periods of darkness. The red dashed lines indicate the deployment and retrieval dates. Red shading indicates periods when the sub-bottom profiler was active.

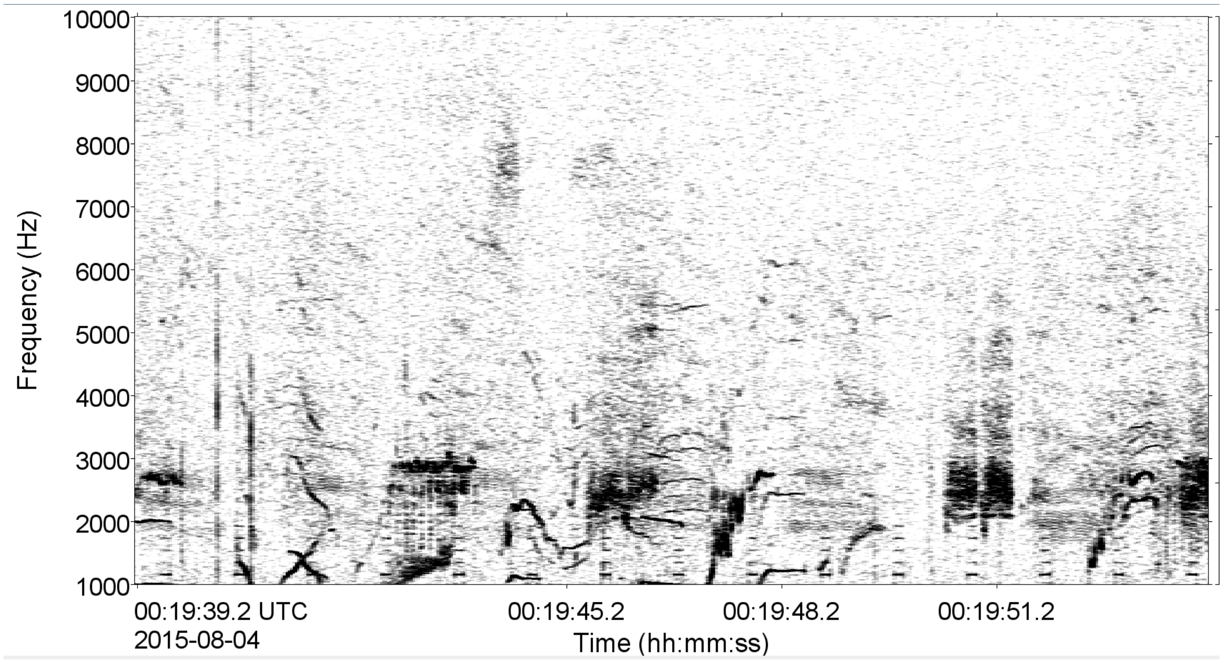

Figure 8. Spectrogram of beluga whale calls recorded at AMAR 1 on 4 Aug 2015 (2 Hz frequency resolution, 0.128 s time window, 0.032 s time step, Hamming window).

3.1.2. Pinnipeds

3.1.2.1. *Bearded seal*

Bearded seal calls were identified once at AMAR 1 on 3 Aug 2015 and once at AMAR 2 on 15 Aug 2015 (Figure 7).

Bearded seal calls included trills previously described for that species (Figure 10; Risch et al. 2007, Frouin-Mouy et al. 2015). Figure 9 is an example of a bearded seal trill (AL7) recorded on AMAR 2.

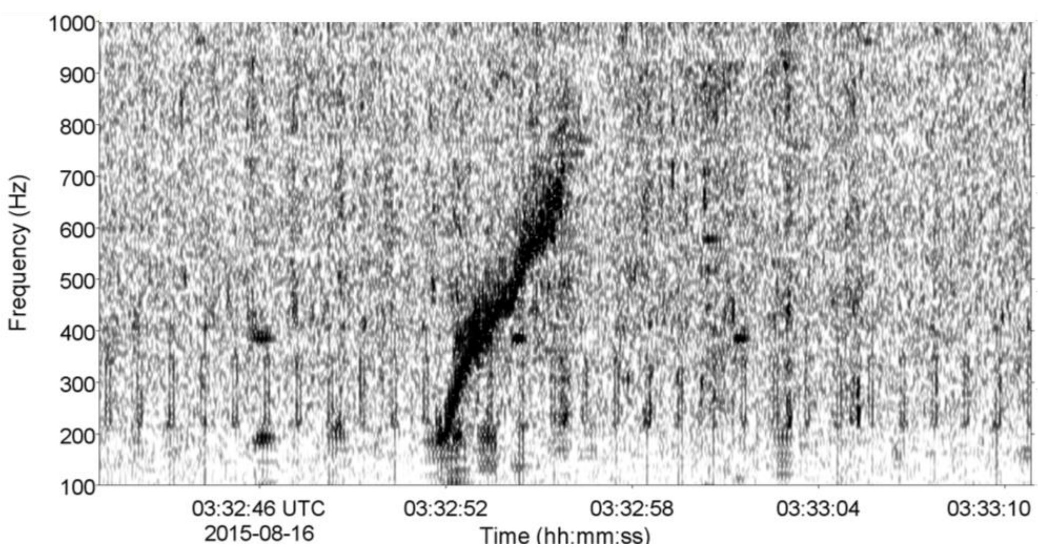

Figure 9. Spectrogram of bearded seal trill (AL7) recorded at AMAR 2 on 15 Aug 2015 (2 Hz frequency resolution, 0.128 s time window, 0.032 s time step, Hamming window).

3.1.2.2. *Unidentified pinnipeds*

Unidentified pinniped vocalizations were frequently detected at both stations; AMAR 1 recorded unidentified pinniped vocalizations (Figure 10) on 10 days (from 7 Jul to 25 Aug 2015) and AMAR 2 on 66 days (from 6 Jul to 21 Sep 2015). Figure 11 shows an example of unidentified pinniped call detected on AMAR 2.

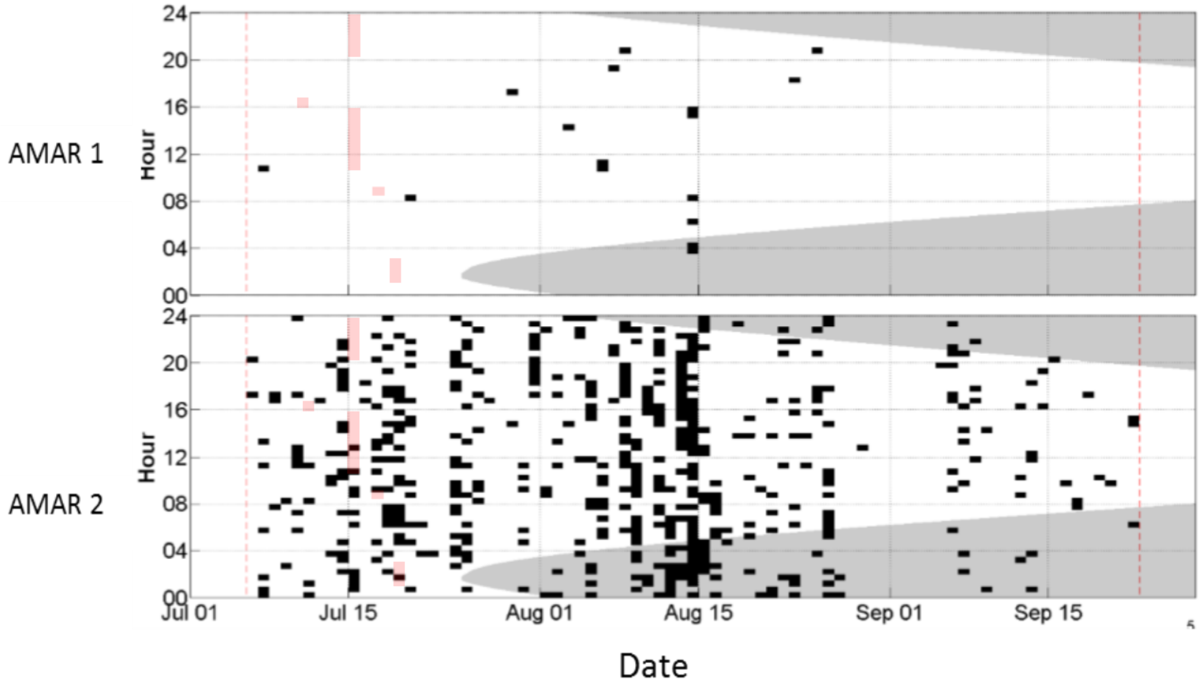

Figure 10. Daily and hourly occurrence of unidentified pinniped calls recorded at AMAR 1 and AMAR 2 from 6 Jul to 22 Sep 2015. Gray shaded areas indicate periods of darkness. The red dashed lines indicate the deployment and retrieval dates. Red shading indicates periods when the sub-bottom profiler was active.

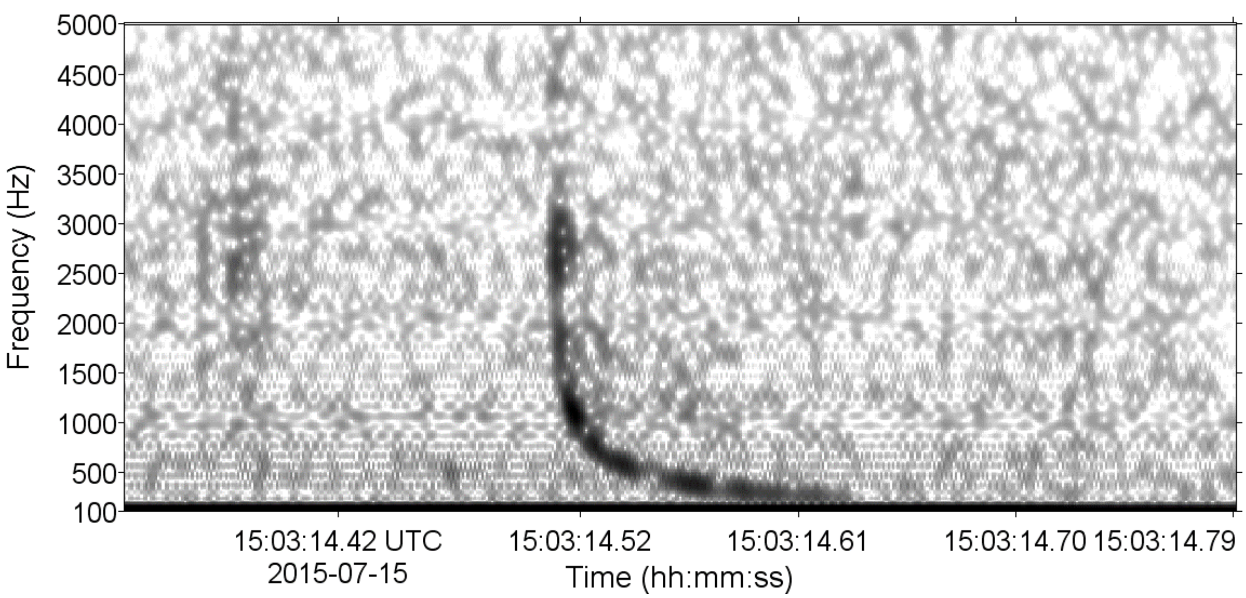

Figure 11. Spectrogram of unidentified pinniped vocalizations recorded at AMAR 2 on 15 Jul 2015 (16 Hz frequency resolution, 0.01 s time window, 0.001 s time step, Hamming window).

3.2. Received Ambient Sound Levels

3.2.1. Total received sound levels

3.2.1.1. *AMAR 1 (500 m)*

Acoustic recordings from AMAR 1 were analyzed to determine power spectral density (PSD) levels and decade band SPLs for the entire recording period. Figure 12 plots the long-term spectrogram (bottom) and decade band levels (top) for the data collected from 6 Jul to 22 Sep 2015. Figure 13 (top) shows the statistical distribution of 1-min average sound pressure levels (SPLs) in each decade band over the monitoring period. The mean 1/3-octave band SPL is higher than the median SPL, which indicates vessel traffic in the area occasionally increased sound levels. Figure 13 (bottom) shows the distribution of 1-min PSD levels over the monitoring period. The daily sound exposure level (SEL) measures accumulated acoustic energy (Figure 14) throughout the recording period; the daily SEL on days in which the sub-bottom profiler was active were no louder than that on days after the survey completed.

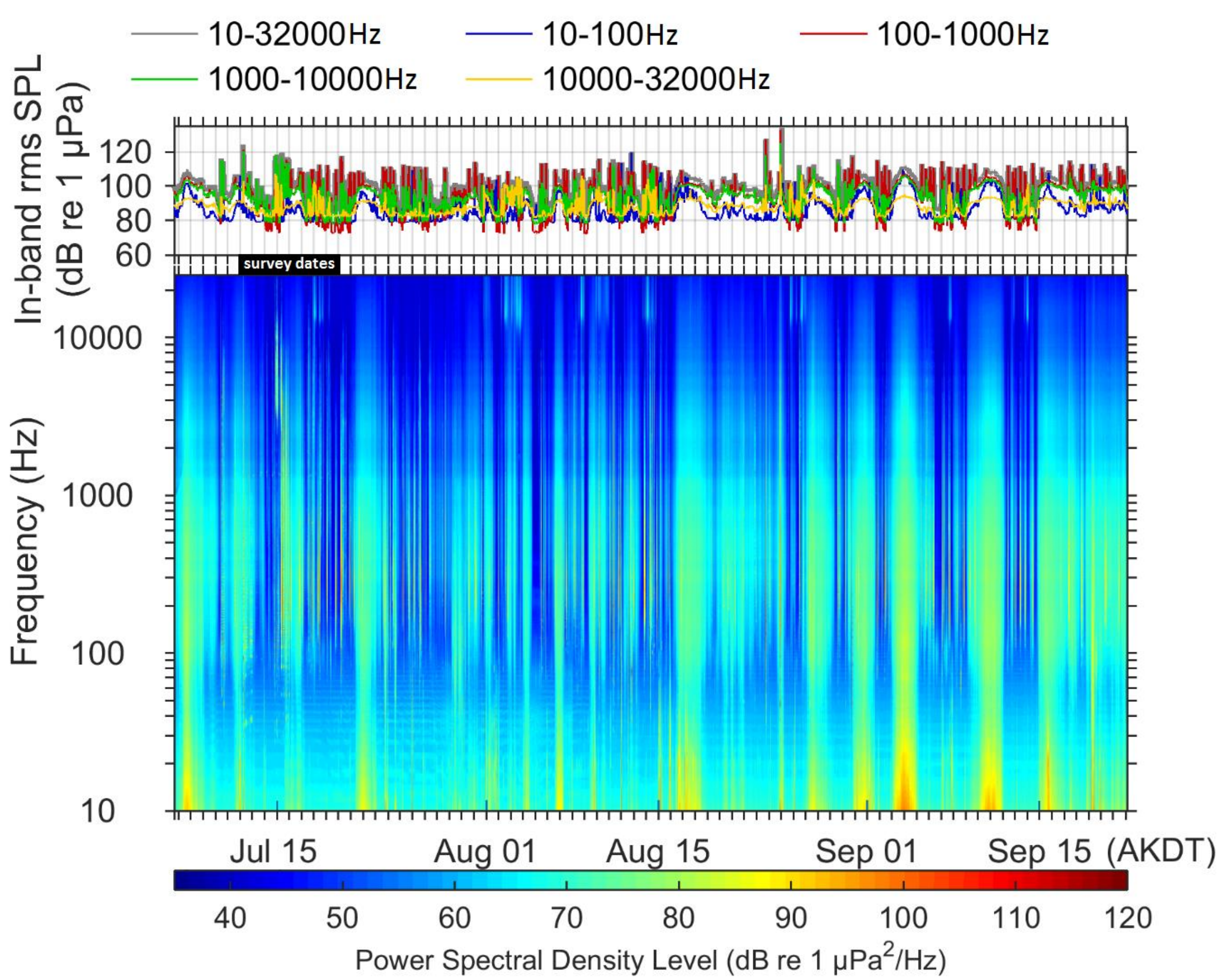

Figure 12. AMAR 1: (Top) Three-month broadband (10 Hz to 32 kHz) SPL and decade band SPL (1-min average) from 6 Jul to 22 Sep 2015. (Bottom) Ambient noise spectrogram (1-min averages) over the same period. Frequency scale is logarithmic.

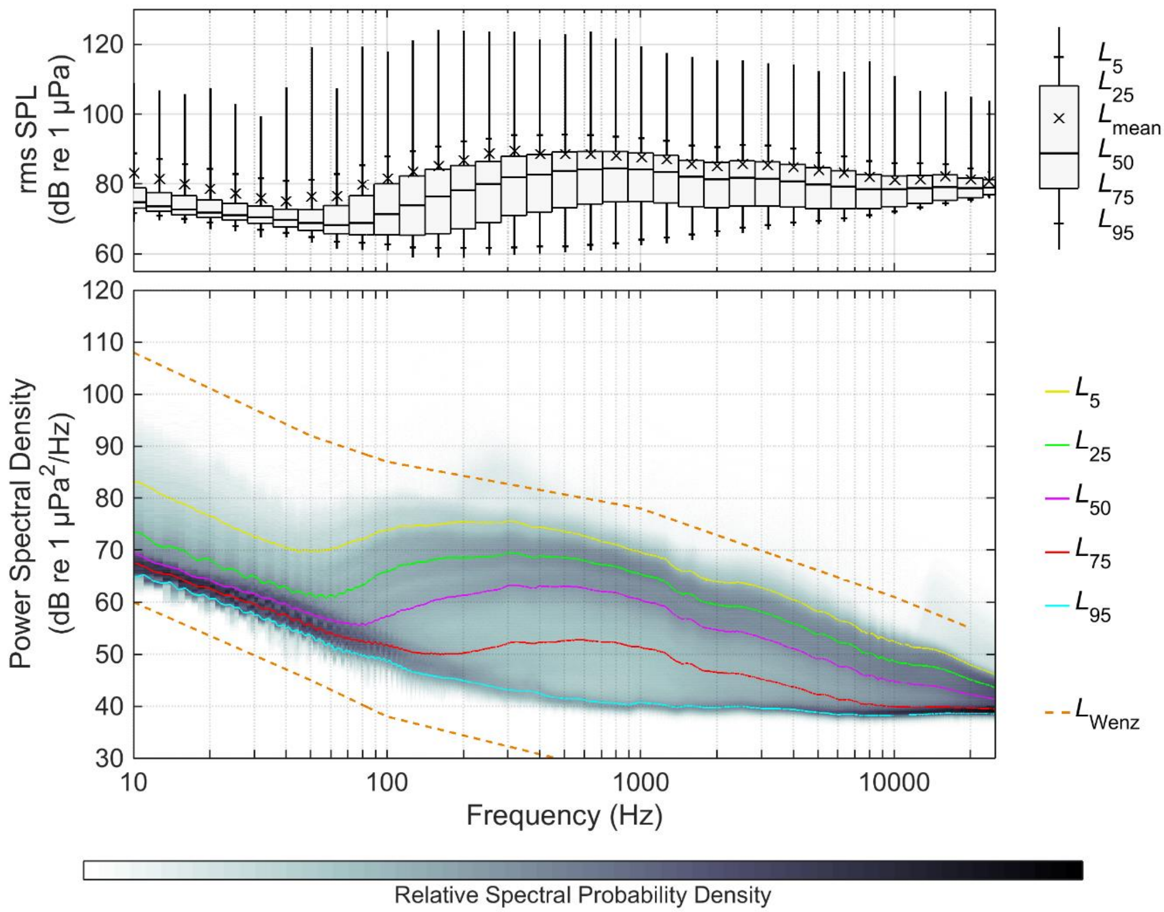

Figure 13. AMAR 1. Statistical distributions of 1/3-octave band and decade band SPLs. (Top) 1/3-octave band rms sound pressure levels (1-min) from 6 Jul to 22 Sep 2015 (three-month) recording period. The boxes indicate the first (25%), second (50%), and third (75%) quartiles. The 'x' indicates the linear mean. (Bottom) Exceedance percentiles of ambient noise power spectral density levels (1-min average) over the recording period. The *N*th percentile corresponds to the sound level that was exceeded by *N*% of the data. The relative spectral probability density is shown in gray scale; the limits of the prevailing noise from the Wenz curves are shown by dashed orange lines (L_{Wenz}).

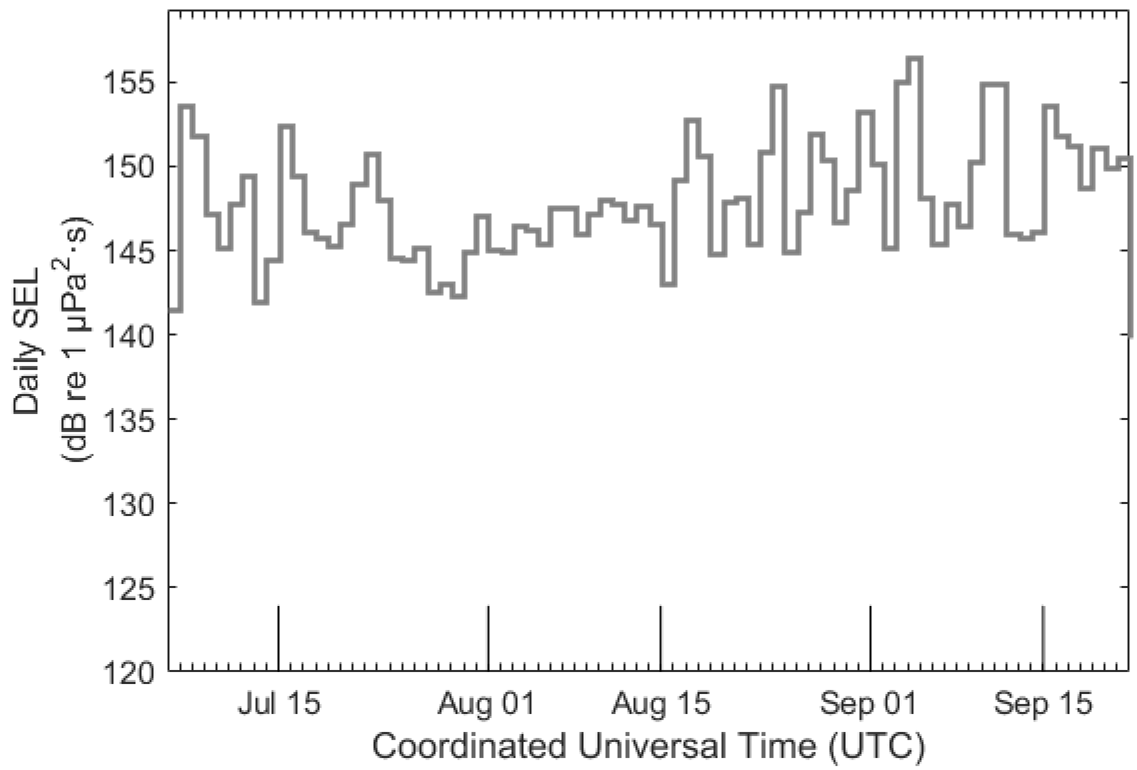

Figure 14. AMAR 1: Daily broadband (10 Hz to 32 kHz) sound exposure level (SEL) from 6 Jul to 22 Sep 2015.

3.2.1.2. *AMAR 2 (5000 m)*

Acoustic recordings from AMAR 2 were analyzed to determine power spectral density (PSD) levels and decade band SPLs for the entire recording period. Figure 15 is a plot of the long-term spectrogram (bottom) and decade band levels (top) for the data collected from 6 Jul to 22 Sep 2015. Figure 16 (top) shows the statistical distribution of 1-min sound pressure levels (SPLs) in each decade band over the monitoring period. The mean 1/3-octave band SPL is higher than the median SPL, which indicates vessel traffic in the area occasionally increased sound levels (see Section 3.2.1.3). Figure 16 (bottom) shows the distribution of 1-min PSD levels over the monitoring period. The daily sound exposure level (SEL) throughout the recording period measures accumulated acoustic energy (Figure 17).

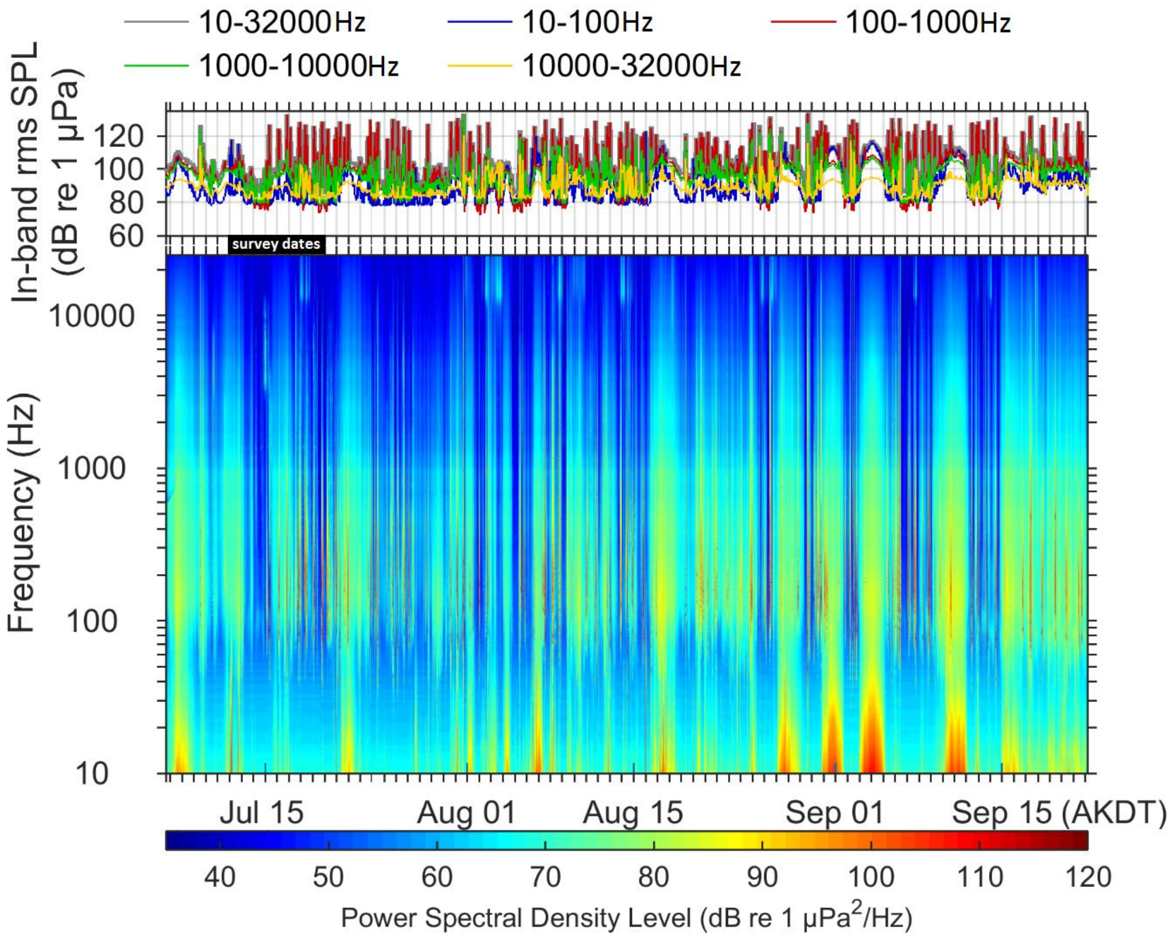

Figure 15. AMAR 2: (Top) Three-month broadband (10 Hz to 32 kHz) SPL and decade band SPL (1-min average) from 6 Jul to 22 Sep 2015 (UTC). (Bottom) Ambient noise spectrogram (1-min average) over the same period. Frequency scale is logarithmic.

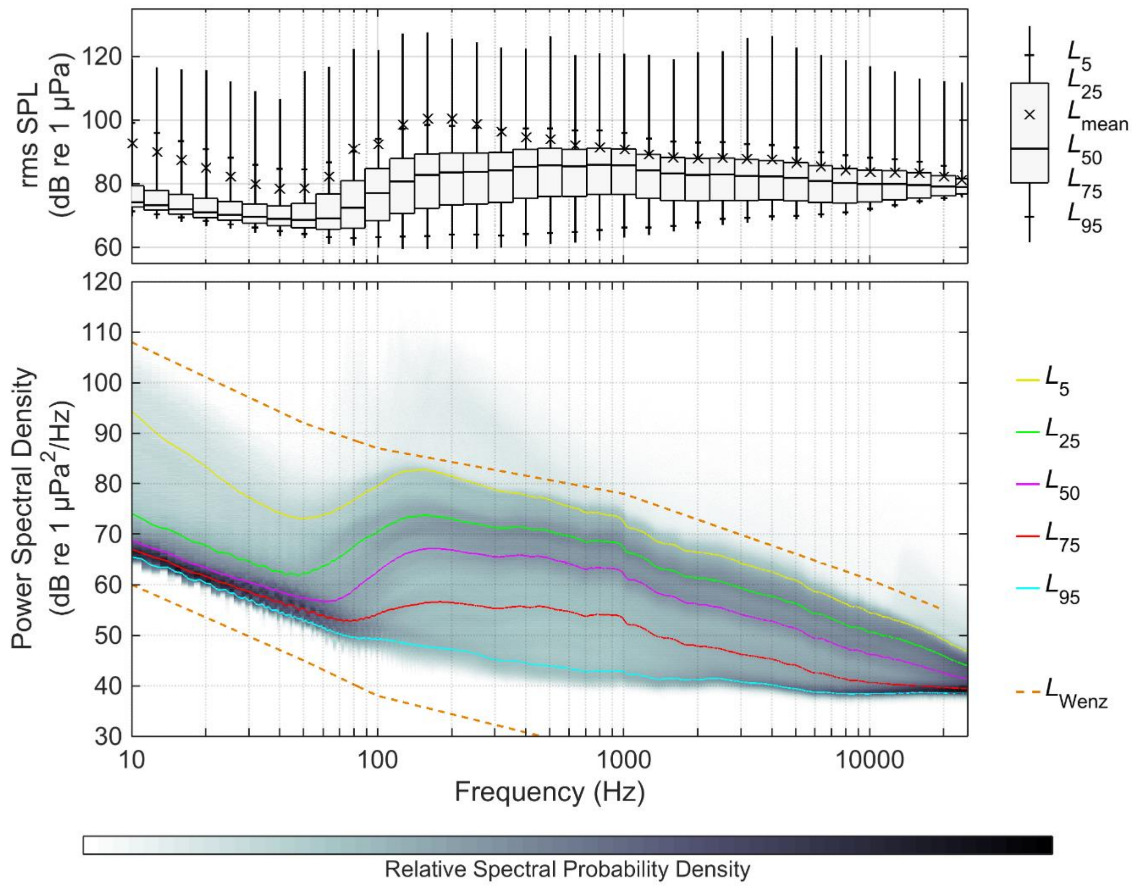

Figure 16. AMAR 2. Statistical distributions of 1/3-octave band and decade band SPLs. (Top) 1/3-octave band rms sound pressure levels (1-min) from 6 Jul to 22 Sep 2015 (three-month) recording period. The boxes indicate the first (25%), second (50%), and third (75%) quartiles. The 'x' indicates the linear mean. (Bottom) Exceedance percentiles of ambient noise power spectral density levels (1-min average) over the recording period. The *N*th percentile corresponds to the sound level that was exceeded by *N*% of the data. The relative spectral probability density is shown in gray scale, and the limits of the prevailing noise from the Wenz curves are shown in the dashed orange lines (L_{Wenz}).

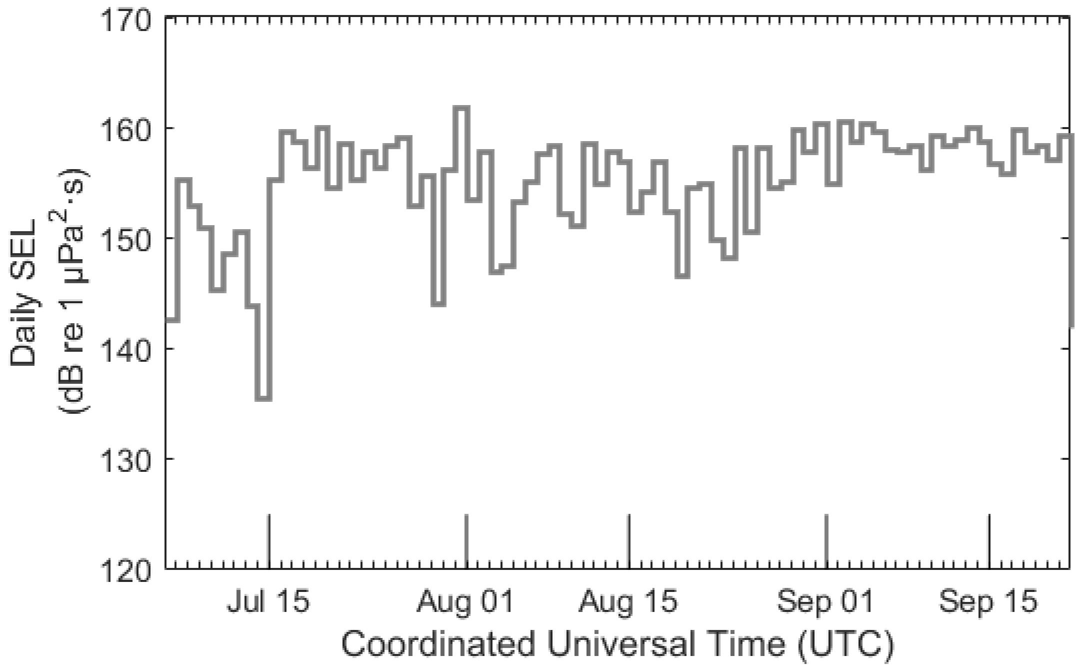

Figure 17. AMAR 1: Daily broadband (10 Hz to 32 kHz) sound exposure level (SEL) from 6 Jul to 22 Sep 2015.

3.2.1.3. *Anthropogenic contribution*

The acoustic recordings were analyzed to determine the contribution of anthropogenic sources to the ambient sound levels. Vessel sounds were detected at both locations (Figure 18) with an average of ~1 hour per day in which vessels were detected (right panels of Figures 19 and 20). This includes all vessel traffic and is not specific to vessels associated with the Hilcorp survey. At AMAR 1 the average daily acoustic energy attributable to passing vessels was ~138 dB SEL (Figure 19), and at AMAR 2 the average daily acoustic energy attributable to passing vessels was ~154 dB SEL (Figure 20). Since the level of occurrence was similar at both recorders, the fact that the average daily SEL was higher at AMAR 2 likely indicates that vessels passed nearer to AMAR 2 compared to AMAR 1. In both cases, the range of sound energy from vessels could almost encompass the range of average daily SEL; meaning that, when present, vessel-associated noise could dominate the ambient soundscape near the vessel.

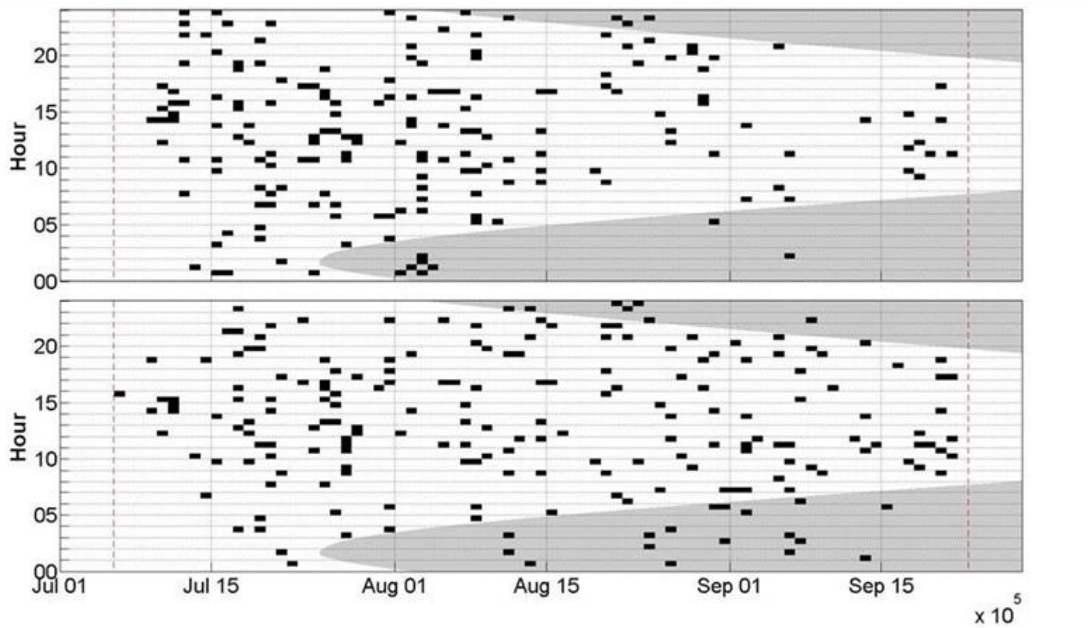

Figure 18. Vessel detections during the recordings for (top) AMAR1 and (bottom) AMAR 2. Gray shaded areas indicate periods of darkness. Black marks indicate half-hour recordings with vessel detections.

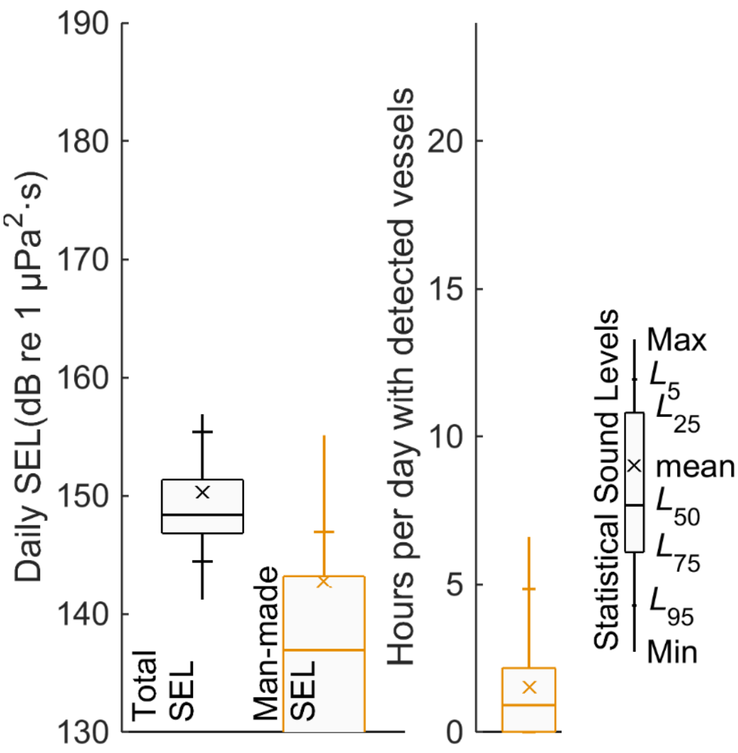

Figure 19. AMAR 1: Contribution of anthropogenic sources (i.e vessels) to daily cumulative ambient sound energy from 6 Jul to 22 Sep 2015. (Left) Statistical description of measured values, see inset, of Daily total SEL and man-made SEL. (Right) Statistical description of number of hours per day vessels were detected.

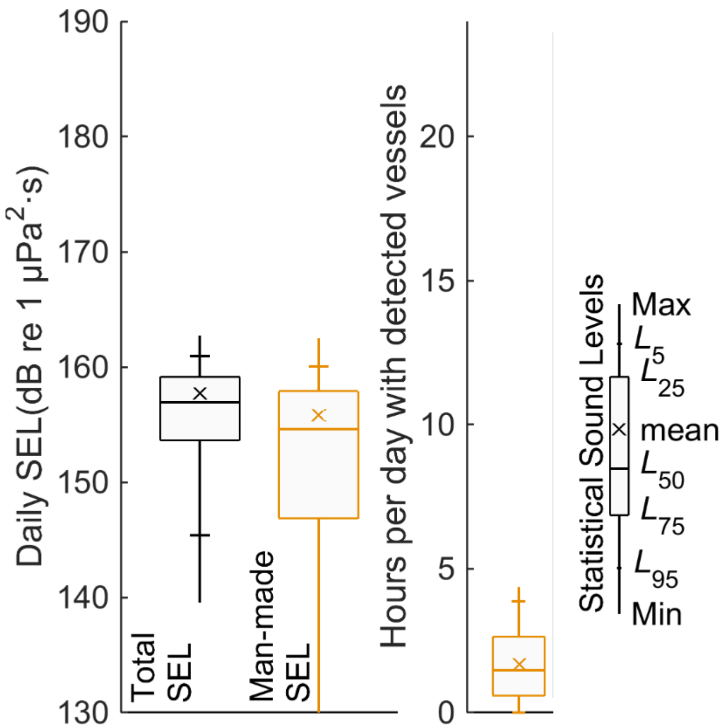

Figure 20. AMAR 2: Contribution of anthropogenic sources (i.e. vessels) to ambient sound energy from 6 Jul to 22 Sep 2015 (three months). (Left) Statistical description of measured values, see inset, of total SEL and man-made SEL. (Right) Statistical description of number of hours per day vessels were detected.

3.2.2. Received Levels during the Survey

The portions of the recordings during the survey, 12–19 Jul, were additionally analyzed to find the power spectral density (PSD) distributions during the survey. Figures 21 and 23 plot the spectrogram (bottom) and decade band levels (top) for AMARs 1 and 2, respectively, showing only the survey period. The sub-bottom profilers were active at times on July 12, 15, 16, 17 and 19 for a total of 14 hours over those days; the one-minute average SPL received on those dates are within the variability of total received sound levels recorded at other times during the survey or after the survey was completed. The statistical distribution of 1-min sound pressure levels (SPLs) in each 1/3-octave band during the survey are shown in the top panels of Figures 22 and 24 for the respective AMARs. As was the case with the three-month recordings, the mean 1/3-octave band SPL is higher than the median SPL because sound level increases from vessels or other survey-associated sounds were infrequent.

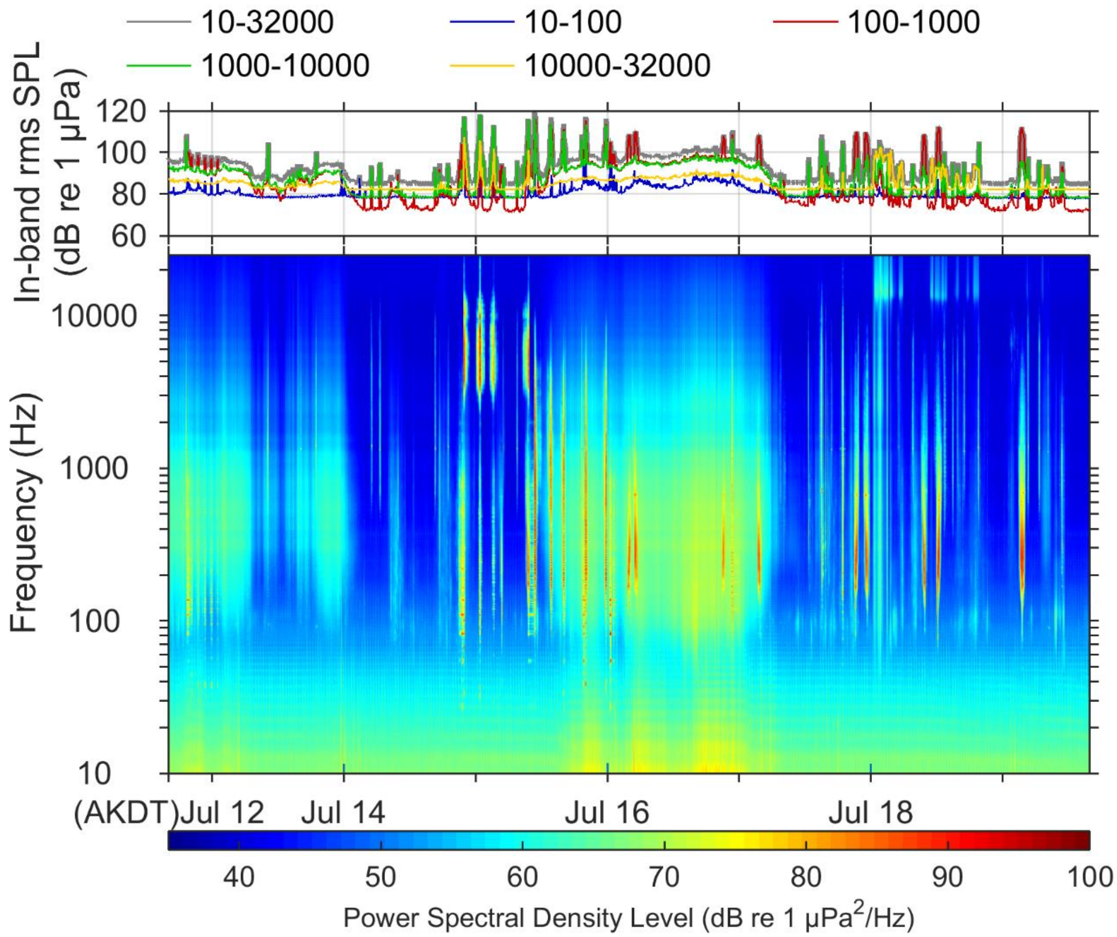

Figure 21. AMAR 1: (Top) Broadband (10 Hz to 32 kHz) SPL and decade band SPL (1-min average) from 12 to 19 Jul 2015 (UTC). (Bottom) Ambient noise spectrogram (1-min average) over the same period. Frequency scale is logarithmic.

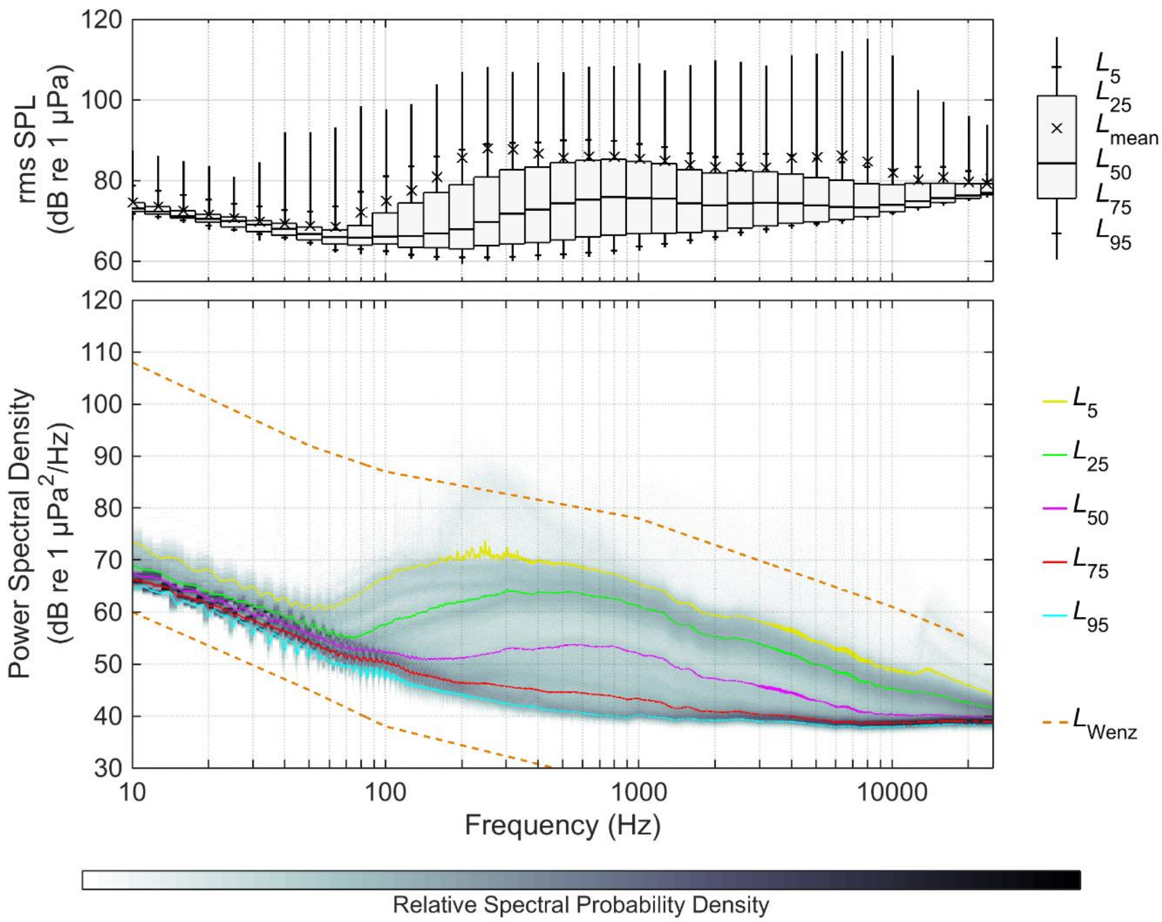

Figure 22. AMAR 1. Statistical distributions of 1/3-octave band SPL and power spectral density. (Top) 1/3-octave band rms sound pressure levels (1-min) during the survey 12–19 Jul (one week). The boxes indicate the first (25%), second (50%), and third (75%) quartiles. The 'x' indicates the linear mean. (Bottom) Exceedance percentiles of ambient noise power spectral density levels (1-min average) over the recording period. The *N*th percentile corresponds to the sound level that was exceeded by *N*% of the data. The relative spectral probability density is shown in gray scale, and the limits of the prevailing noise from the Wenz curves are shown in the dashed orange lines (L_{Wenz}).

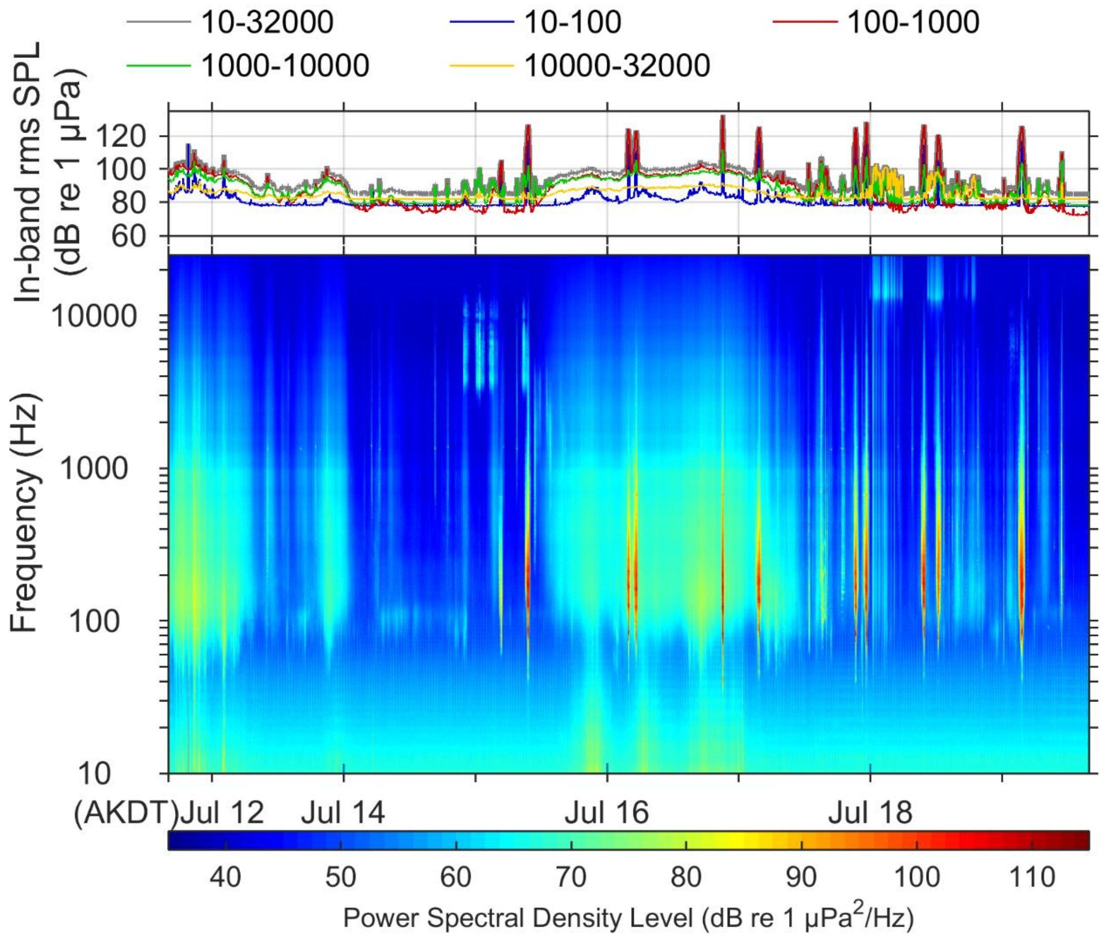

Figure 23. AMAR 2: (Top) Broadband (10 Hz to 32 kHz) SPL and decade band SPL (1-min average) from 12–19 Jul 2015 (UTC). (Bottom) Ambient noise spectrogram (1-min average) over the same period. Frequency scale is logarithmic.

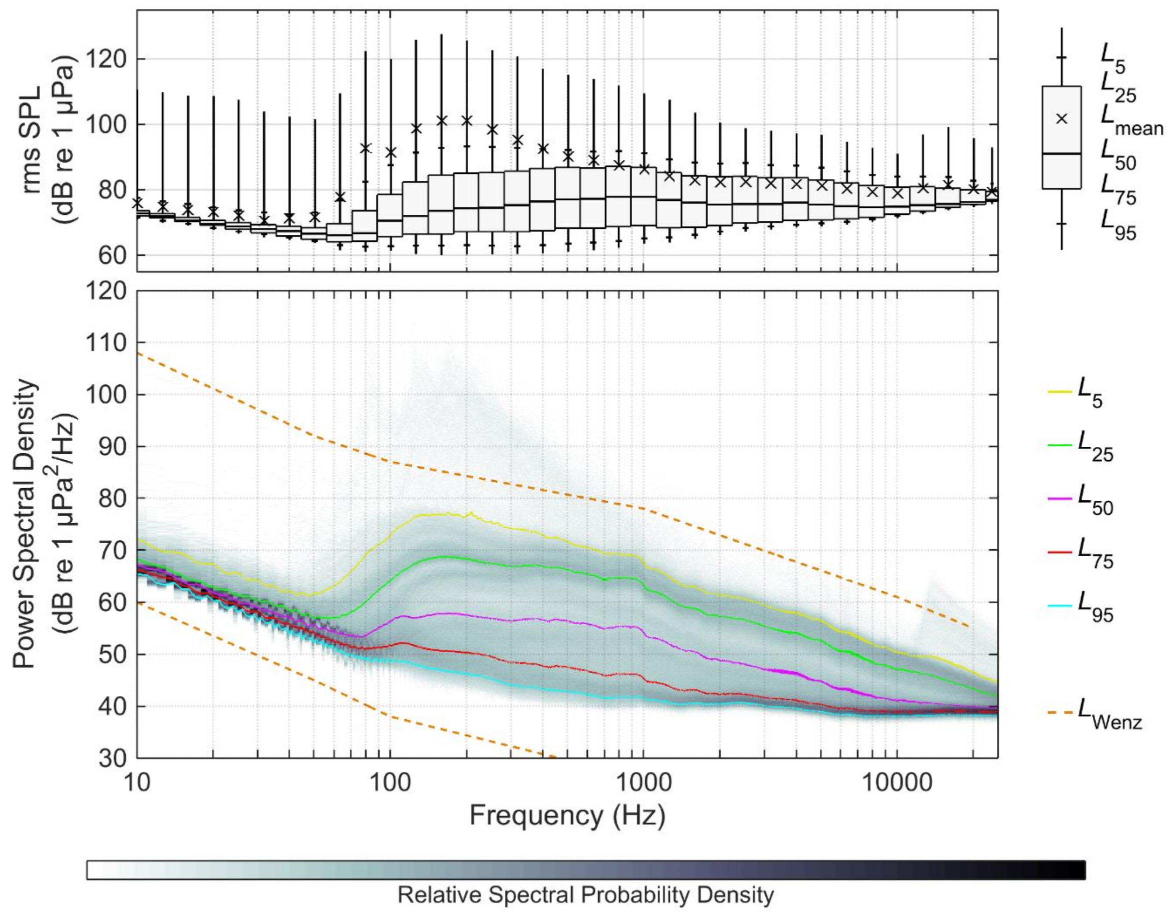

Figure 24. AMAR 2. Statistical distributions of 1/3-octave band SPL and power spectral density. (Top) 1/3-octave band rms sound pressure levels (1-min) during the survey 12–19 Jul (one week). The boxes indicate the first (25%), second (50%), and third (75%) quartiles. The ‘x’ indicates the linear mean. (Bottom) Exceedance percentiles of ambient noise power spectral density levels (1-min average) over the recording period. The *N*th percentile corresponds to the sound level that was exceeded by *N*% of the data. The relative spectral probability density is shown in gray scale, and the limits of the prevailing noise from the Wenz curves are shown in the dashed orange lines (L_{Wenz}).

4. Discussion

4.1. Marine Mammal Vocalizations

The analysis of acoustic data recorded at both stations in Foggy Island Bay revealed the acoustic occurrence of beluga whales and several species of pinnipeds including bearded seals. These detections are discussed in the context of current information derived from previous surveys and from the visual survey that occurred during Hilcorp's shallow geohazard survey in Foggy Island Bay, 9–19 Jul 2015.

It should be noted that sounds below 1 kHz (typical of mysticetes) have significantly less seawater absorption loss than sounds above 10 kHz (typical of odontocetes), and thus can be detected at greater distances (Mellinger et al. 2004). It is common to detect mysticete vocalisations at ranges of several tens of kilometres on a single hydrophone (Stafford et al. 2007a), while odontocete clicks and whistles can be detected at ranges of 1–6 km (Quintana-Rizzo et al. 2006, Wang et al. 2006, Jensen et al. 2012, Ainslie 2013).

4.1.1. Beluga whales

Beluga whales were the only cetaceans detected. Some detections match observations on 14 Jul during Hilcorp's shallow geohazard survey in Foggy Island Bay (Cate et al. 2015). In the Alaskan Arctic during both summer and fall, beluga whales select outer shelf and slope waters and moderate to heavy ice conditions (Moore et al. 2000), so we believe these results accurately describe this species' rare occurrence in the study area.

4.1.2. Bearded seals

Bearded seals were the only positively identified pinniped species in our dataset. Bearded seal detections occurred only on two different occasions (3 Aug at AMAR 1 and 15 Aug at AMAR 2). Bearded seals are widely distributed throughout the circumpolar Arctic, mainly in the relatively shallower waters of the continental shelf and usually in association with moving ice (Burns 1970). However, they are thought to be mainly pelagic during the summer and fall. Bearded seals are least vocally active from late June to September (Frouin-Mouy et al. 2015), which could explain the paucity of their acoustic detections in this study.

4.1.3. Unidentified pinniped species

Spotted and ringed seals were not manually or automatically detected in the summer 2015 datasets, likely because we do not have a good representation of their call types (Stirling 1973, Beier and Wartzok 1979, Jones et al. 2014). Both species were regularly seen in the area by protected species observers from the M/V *Journey* during Hilcorp's shallow geohazard survey in Foggy Island Bay, 9–19 Jul 2015 (Cate et al. 2015). We assumed that the unidentified pinniped vocalizations manually detected in our dataset were actually produced by spotted and/or ringed seals, which means that one or both species were in the area throughout the recording period.

4.2. Total Received Sound Levels and Geohazard Survey Sound Levels

Wenz (1962) provided a distribution of ambient sound levels as a function of frequency for a range of sea state conditions, commonly referred to as the Wenz curves (Appendix A.2). The dashed lines in the power spectral density plots (PSD, Figures 13 and 16) are the limits of the Wenz curves for low and high sea states. Because the PSD distributions for each AMAR fall within these limits, they are within the expected range for ambient sound levels. The PSD distributions also decay with increasing frequency at a rate consistent with the rate of decay described by Wenz, which indicates that weather is a primary driver of sound levels at these locations.

Figure 25 is a plot of the wind speed recorded at the Deadhorse Airport during the acoustic monitoring period; wind speed data were not available prior to Aug 8 (NOAA National Data Buoy Center, Station PRDA2; www.ndbc.noaa.gov, accessed Feb 25, 2016). Although underwater ambient sound pressure levels do not correlate exactly with wind speed, fluctuations of wind speed correspond with delayed fluctuations of sea state that do tend to correlate with underwater received sound levels. The fluctuations of the average received SPLs (Figure 15 and Figure 17) do generally track the wind speed fluctuations and periods of increased ambient sound levels occurred following high wind-speed events such as those on 01, 04 and 11 Sep.

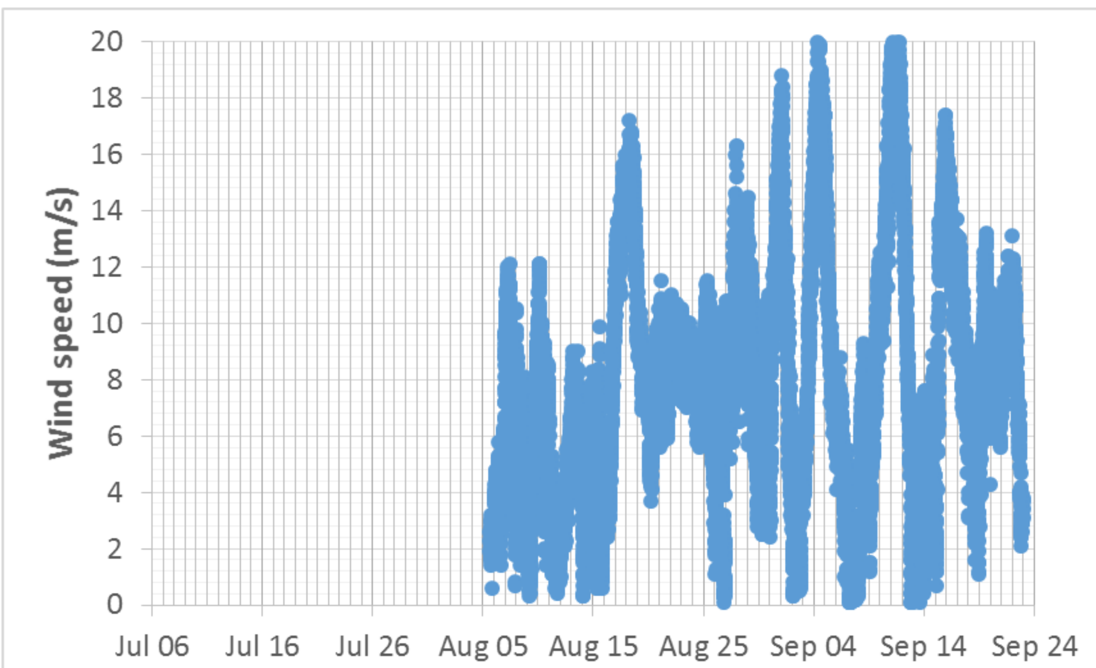

Figure 25. Wind speed recorded at the Prudhoe Bay Airport, NOAA National Data Buoy Center Station PRDA2.

Typically, the sound levels were higher at AMAR 2 than AMAR 1 (Section 3.2.1). Figure 26 is a plot of the probability distribution of broadband received sound levels at AMAR 1 and AMAR 2, which highlights this trend. This analysis showed that 10% of the time the sound levels exceeded 104 dB re 1 µPa and 108 dB re 1 µPa, with median levels of 96 and 98 dB re 1 µPa at AMAR 1 and AMAR 2, respectively. AMAR 2 was located further from the survey, in the offshore direction, so the higher received levels at AMAR 2 could be attributed to offshore sound sources. These levels are consistent with a median ambient level of 97 dB re 1 µPa (20–5000 Hz) measured over 44 days at Liberty in 1998 (Greene 1998). Greene reported a 95th percentile ambient sound level of 78 dB re 1 µPa, which is lower than the minimum SPL measured in this study. But, the 1998 data did not include the full acoustic bandwidth that was achieved in the present study, i.e. the 1998 measurements did not account for acoustic energy at frequencies from 10 to 20 Hz and from 5 to 32 kHz as did the data in the present study.

Vessel traffic noise, which contributes to the overall noise levels, was recorded on both AMARs (Figure 18). At AMAR 1 the average acoustic energy attributable to passing vessels was ~10 dB lower than the total daily SEL (Figure 19). At AMAR 2 the average acoustic energy attributable to passing vessels was ~2 dB lower than the total daily SEL (Figure 20), which means vessel noise contributes more to the soundscape at AMAR 2 than AMAR 1, and that vessel noise likely accounts for most of the difference in the sound energy levels between AMAR 1 and AMAR2.

Vessels are identifiable by noise produced between 100 to 300 Hz. The sound-level percentile values are increased in this frequency band (Figures 13 and 16) which is consistent with the contribution of vessel noise to the overall sound levels. The fact that the relative spectral probability density (gray cloud) exceeded the weather-driven Wenz curve upper limits in this frequency band also exemplifies this phenomenon. The exceedance was greater at AMAR 2 than at AMAR 1.

To characterize the long range propagation of sound from the geohazard survey, we examined the average broadband and decade band sound levels during the week-long survey (12–19 Jul) and found they were similar or lower than levels determined for the entire three-month recording (7 Jul to 22 Sep) (Figure 27). Table 4 shows that the mean, hourly-averaged, broadband sound levels during the survey (12–19 Jul) were no higher than those recorded after the survey (20 Jul to 22 Sep).

Figure 28 is a plot of 1 second of data recorded on AMAR 1 during a period in which the AA251 sub-bottom profiler was active at a range of 575 m from the AMAR. The client-specified operating frequency for the AA251 was 1–4 kHz but the individual pulses contained sound energy to frequencies below 200 Hz. Sound levels for the individual pulses were not characterized for this report but the times that the sub-bottom profilers were active were included in the statistical distributions shown above. The sub-bottom profilers operated intermittently, often turning on and off at intervals of a few minutes, and were active for a total of only 14 hours during the survey. Therefore, the mean sound levels reported in this Section underestimate the SPL of the individual pulses, through averaging. Nevertheless, the maximum broadband SPL recorded during the survey fell within the range of variability of the levels recorded during the full acoustic monitoring period, indicating that noise from the survey vessels and sub-bottom profilers did not appreciably increase the overall acoustic environment at distances greater than 500 m from the survey activities.

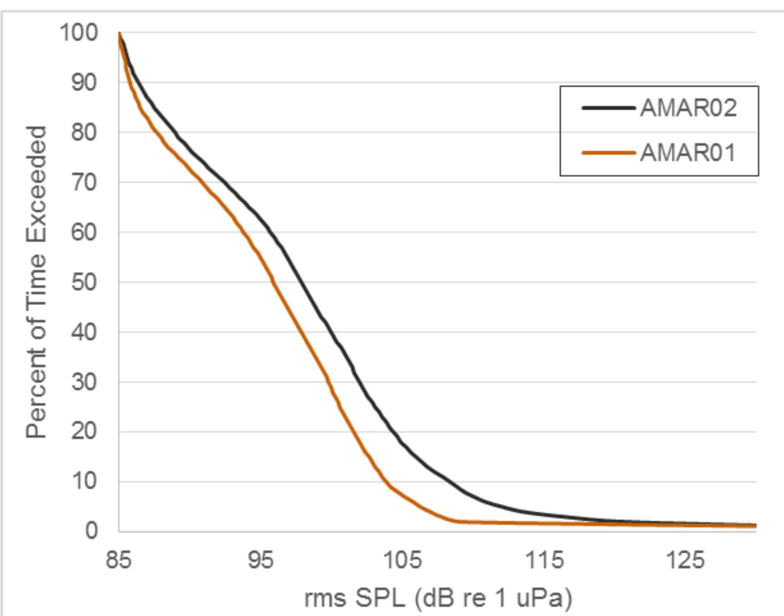

Figure 26. Probability distribution of broadband ambient SPLs (10 Hz to 32 kHz) measured over the three months period 6 Jul to 22 Sep 2015 at AMAR 1 (500 m) and AMAR 2 (5000 m).

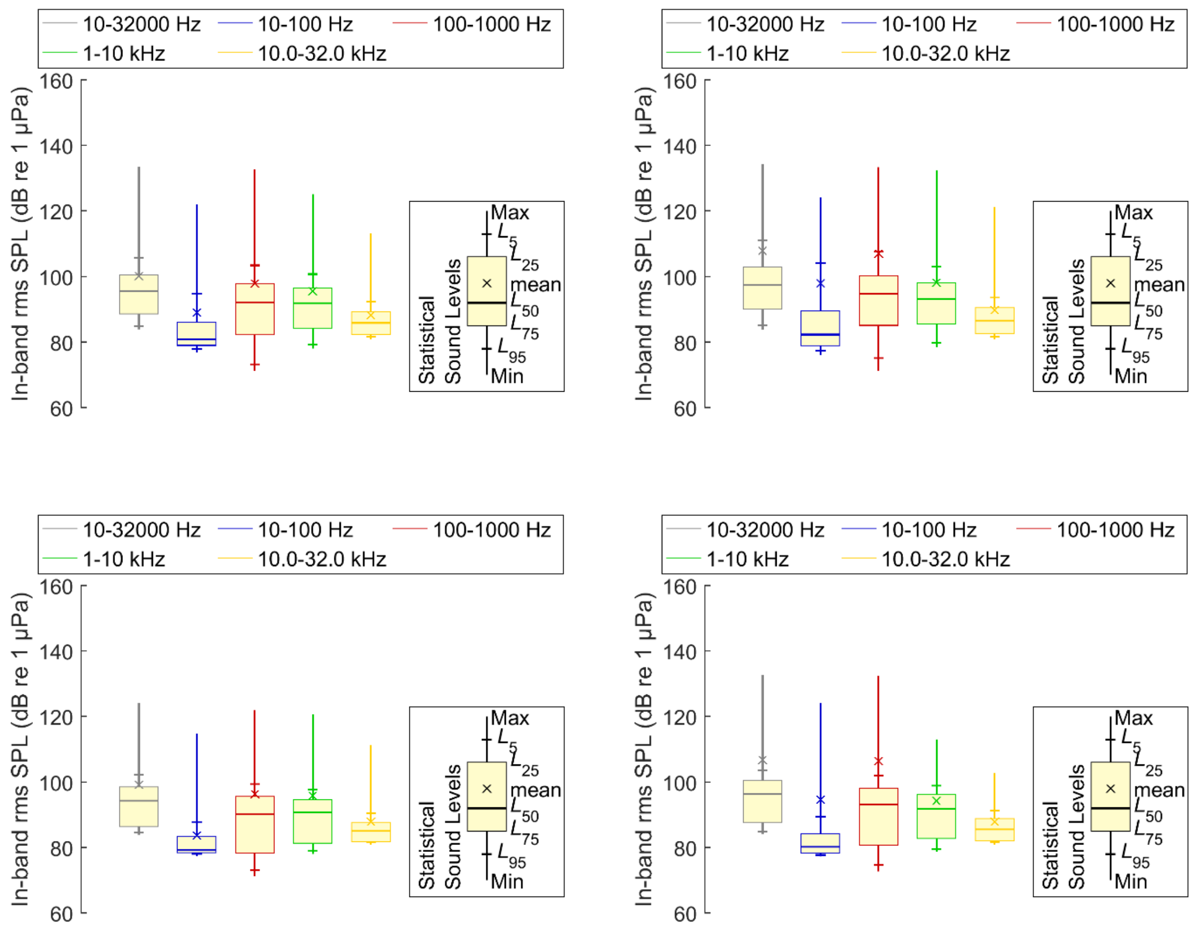

Figure 27. Broadband and decade band statistical distribution of SPLs. (Top)Three-month duration of recordings, 6 Jul–22 Sep 2015 (AMAR 1 top, left; AMAR 2 top, right). (Bottom) During survey operations, 12–19 Jul 2015 (AMAR 1 bottom, left; AMAR 2 bottom, right).

Table 4. Sound levels during and after the survey: Broadband (10 Hz to 32 kHz) average ± standard deviation of the hourly-averaged rms SPL dB re 1 µPa sound levels at AMAR 1 and AMAR 2 during the survey 12–19 Jul and after the survey 20 July to 22 September.

Location	Date	10 Hz-33 kHz
AMAR 1 (500 m)	12-19 Jul	92.7 ± 6.6
	20 Jul–22 Sep	94.8 ± 6.9
AMAR 2 (5000 m)	12-19 Jul	95.9 ± 6.8
	20 Jul–22 Sep	99.6 ± 7.2

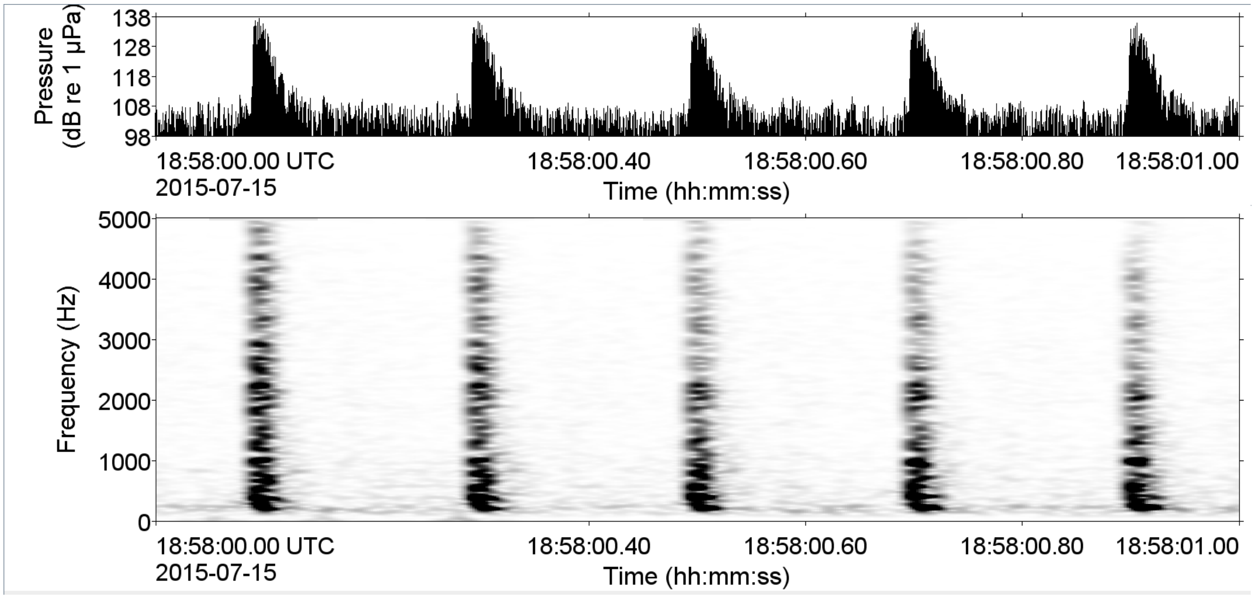

Figure 28. Example recording from AMAR 1 of noise from the AA251 sub-bottom profiler (the lowest-frequency source used during the survey) recorded at 575 m range. (Top) Broadband received sound pressure and (bottom) spectral content.

5. Summary

Acoustic monitoring was conducted between 6 Jul and 22 Sep, 2015 to characterize ambient sound conditions and to determine occurrence of marine mammals near to Hilcorp's Liberty prospect in Foggy Island Bay, AK. Two AMAR recorders collected underwater sound data before, during, and after Hilcorp's 2015 geohazard survey.

Detected marine mammal vocalizations included those from belugas and pinnipeds. Belugas were only detected on five days and pinnipeds were detected more frequently (10 days on the nearshore AMAR 1 and 66 days at AMAR 2, further from shore). Bearded seal vocalizations were detected on two days, with unidentified pinnipeds comprising the remaining detections.

The median, broadband ambient sound levels were 96 and 98 dB re 1 µPa on AMAR 1 and AMAR 2, respectively. Statistical distribution of the ambient sound levels with frequency generally followed the expected trends for weather-driven ambient sound conditions with occasional influence from vessel noise. Sound levels recorded on the AMARs during Hilcorp's geohazard survey were no louder than those recorded after the survey was complete. Vessel noise and noise from the sub-bottom profiler were detectable during the survey. However, at the measurement locations (i.e. at ranges greater than 500 m from the survey activities) these sources did not result in statistically notable sound level excursions in excess of the measured variability of local non-survey sound levels due to weather events or unrelated vessel noise. Noise from the survey vessels and sub-bottom profilers did not appreciably alter the local soundscape measured at ranges greater than 500 m from the survey activities.

Glossary

1/3-octave band
Non-overlapping passbands that are one-third of an octave wide (where an octave is a doubling of frequency). Three adjacent 1/3-octave bands make up one octave. Third-octave-bands become wider with increasing frequency. See also octave.

ambient noise
All-encompassing sound at a given place, usually a composite of sound from many sources near and far (ANSI S1.1-1994 R2004), e.g., shipping vessels, seismic activity, precipitation, sea ice movement, wave action, and biological activity.

anthropogenic
Originating in human activity

background noise
Total of all sources of interference in a system used for the production, detection, measurement, or recording of a signal, independent of the presence of the signal (ANSI S1.1-1994 R2004). Ambient noise detected, measured, or recorded with a signal is part of the background noise.

broadband sound level
The total sound pressure level measured over a specified frequency range. If the frequency range is unspecified, it refers to the entire measured frequency range.

decibel (dB)
One-tenth of a bel. Unit of level when the base of the logarithm is the tenth root of ten, and the quantities concerned are proportional to power (ANSI S1.1-1994 R2004).

duty cycle
The time when sound is periodically recorded by an acoustic recording system.

fast Fourier transform (FFT)
A computationally efficiently algorithm for computing the discrete Fourier transform.

frequency
The rate of oscillation of a periodic function measured in cycles-per-unit-time. The reciprocal of the period. Unit: hertz (Hz). Symbol: f. 1 Hz is equal to 1 cycle per second.

hertz (Hz)
A unit of frequency defined as one cycle per second.

hydrophone
An underwater sound pressure transducer. A passive electronic device for recording or listening to underwater sound.

median
The 50th percentile of a statistical distribution.

octave
The interval between a sound and another sound with double or half the frequency. For example, one octave above 200 Hz is 400 Hz, and one octave below 200 Hz is 100 Hz.

percentile level, exceedance
The sound level exceeded *n*% of the time during a measurement.

phocid
A common term used to describe all members of the family Phocidae. These true/earless seals are more adapted to in-water life than are otariids, which have more terrestrial adaptations. Phocids use their hind flippers to propel themselves. Phocids are one of the three main groups in the superfamily Pinnipedia; the other two groups are otariids and walrus.

power spectrum density
The acoustic signal power per unit frequency as measured at a single frequency. Unit: $\mu Pa^2/Hz$, or $\mu Pa^2 \cdot s$.

power spectral density level
The decibel level ($10\log_{10}$) of the power spectrum density, usually presented in 1 Hz bins. Unit: dB re 1 $\mu Pa^2/Hz$.

pressure, acoustic
The deviation from the ambient hydrostatic pressure caused by a sound wave. Also called overpressure. Unit: pascal (Pa). Symbol: *p*.

pressure, hydrostatic
The pressure at any given depth in a static liquid that is the result of the weight of the liquid acting on a unit area at that depth, plus any pressure acting on the surface of the liquid. Unit: pascal (Pa).

pulsed sound
Discrete sounds with durations less than a few seconds. Sounds with longer durations are called continuous sounds.

received level
The sound level measured at a receiver.

rms
root-mean-square.

sound
A time-varying pressure disturbance generated by mechanical vibration waves travelling through a fluid medium such as air or water.

sound exposure level (SEL)
A measure related to the sound energy in one or more pulses. Unit: dB re 1 $\mu Pa^2 \cdot s$.

sound intensity
Sound energy flowing through a unit area perpendicular to the direction of propagation per unit time.

spectrogram
A visual representation of acoustic amplitude versus time and frequency.

spectrum
An acoustic signal represented in terms of its power (or energy) distribution versus frequency.

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Appendix A. Acoustic Theory

A.1. Acoustic Sound Level Metrics

Underwater sound amplitude is measured in decibels (dB) relative to a fixed reference pressure of p_0 = 1 μPa. Because the loudness of impulsive noise, from seismic airguns and sonar for example, is not generally proportional to the instantaneous acoustic pressure, several sound level metrics are commonly used to evaluate the loudness of impulsive noise and its effects on marine life.

The zero to-peak SPL, or peak SPL (dB re 1 μPa), is the maximum instantaneous sound pressure level in a stated frequency band attained by an acoustic pressure signal, $p(t)$:

$$\text{Peak SPL} = 10\log_{10}\left[\frac{\max\left(\left|p^2(t)\right|\right)}{p_0^2}\right] \tag{A-1}$$

The peak SPL metric is commonly quoted for impulsive sounds, but it does not account for the duration or bandwidth of the noise. At high intensities, the peak SPL can be a valid criterion for assessing whether a sound is potentially injurious; however, because the peak SPL does not account for the duration of a noise event, it is a poor indicator of perceived loudness.

The root-mean-square (rms) SPL (dB re 1 μPa) is the rms pressure level in a stated frequency band over a time window (T, s) containing the acoustic event:

$$\text{rms SPL} = 10\log_{10}\left(\frac{1}{T}\int_T p^2(t)dt \Big/ p_0^2\right) \tag{A-2}$$

The rms SPL is a measure of the average pressure or of the effective pressure over the duration of an acoustic event, such as the emission of one acoustic pulse, a marine mammal vocalization, the passage of a vessel, or a fixed duration.

The sound exposure level (SEL, dB re 1 μPa^2·s) is a measure of the total acoustic energy contained in one or more acoustic events. The SEL for a single event is computed from the time-integral of the squared pressure over the full event duration (T_{100}):

$$\text{SEL} = 10\log_{10}\left(\int_{T_{100}} p^2(t)dt \Big/ T_0 p_0^2\right) \tag{A-3}$$

where T_0 is a reference time interval of 1 s. The SEL represents the total acoustic energy received at some location during an acoustic event; it measures the total sound energy to which an organism at that location would be exposed.

To compute the SPL and SEL of acoustic events in the presence of high levels of background noise, Equations A-2 and A-3)are modified to subtract the background noise energy from the event energy:

$$\text{rms SPL} = 10\log_{10}\left(\frac{1}{T_{90}}\int_{T_{90}} (p^2(t)-\overline{n^2})dt \Big/ p_0^2\right) \tag{A-4}$$

$$\text{SEL} = 10\log_{10}\left(\int_{T_{100}} (p^2(t)-\overline{n^2})dt \Big/ T_0 p_0^2\right) \tag{A-5}$$

where $\overline{n^2}$ is the mean square pressure of the background noise generally computed by averaging the squared pressure of a nearby segment of the acoustic recording during which acoustic events are absent (e.g., between pulses).

Because the rms SPL and SEL are both computed from the integral of square pressure, these metrics are related by a simple expression, which depends only on the duration of the energy time window *T*:

$$\text{rms SPL} = \text{SEL} - 10\log_{10}(T) \tag{A-6}$$

The peak-to-peak SPL (dB re 1 µPa) is the difference between the maximum and minimum instantaneous sound pressure levels in a stated frequency band attained by an impulse, *p*(*t*):

$$\text{Peak-to-peak SPL} = 10\log_{10}\left\{\frac{\left[\max(p(t)) - \min(p(t))\right]^2}{p_0^2}\right\} \tag{A-7}$$

A.2. Total Sound Levels: Spectral and Band Level Analysis

The distribution of a sound's power with frequency is described by the sound's spectrum, which shows the fine-scale features of the frequency distribution of a sound. The sound spectrum can be split into a series of adjacent frequency bands. Splitting a spectrum into 1 Hz wide bands, called passbands, yields the "power spectral density" of the sound. These values directly compare to the Wenz curves that represent typical deep ocean sound levels (Figure A-1; Wenz 1962) .

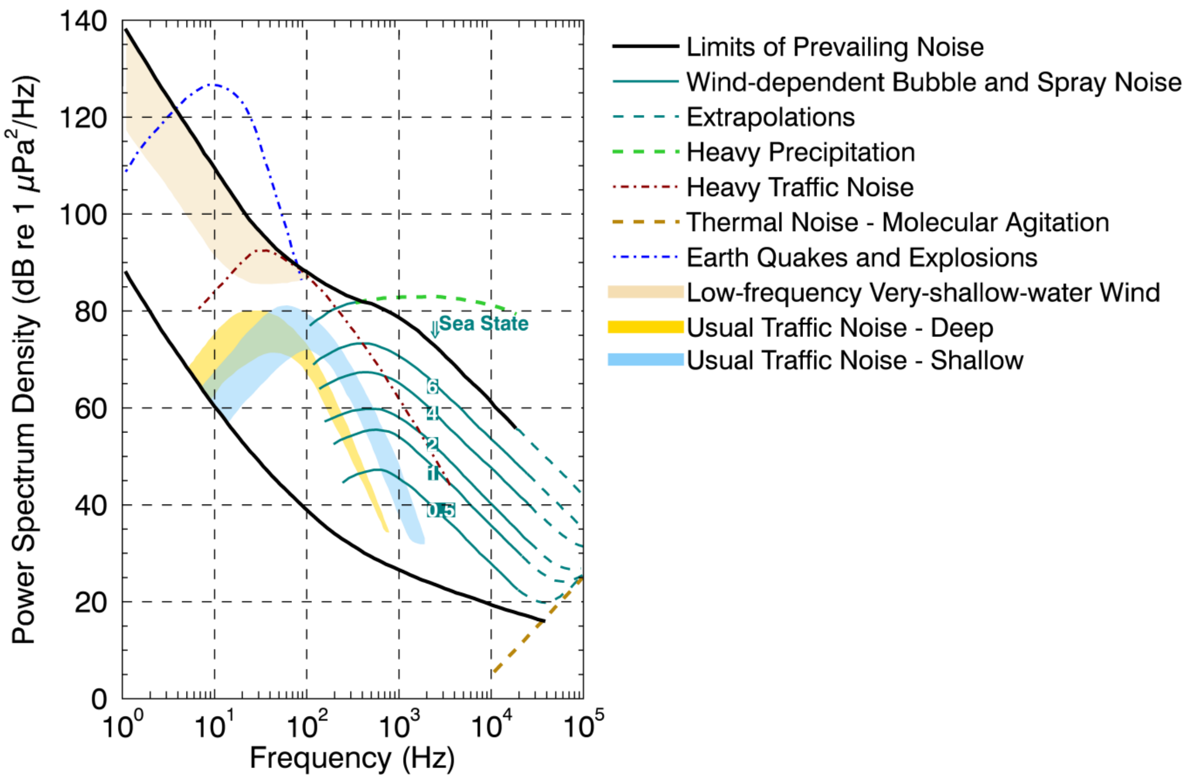

Figure A-1. Wenz curves describing pressure spectral density levels of marine ambient noise from weather, wind, geologic activity, and commercial shipping (Wenz 1962) and typical source spectra of anthropogenic sound sources (Ross 1976, Urick 1983, Scrimger and Heitmeyer 1991, Erbe and Farmer 2000, Erbe 2002b, 2002a, 2009). The limits of prevailing noise of the Wenz curves (thick black lines) are plotted as orange dashed lines on the ambient sound.

Because animals perceive exponential increases in frequency rather than linear increases, analyzing a sound spectrum with passbands that increase exponentially in size gives data that are more meaningful. In underwater acoustics, a spectrum is commonly split into 1/3-octave bands, which are one-third of an octave wide; each octave represents a doubling in sound frequency. The center frequency of the ith 1/3-octave band, $f_c(i)$, is defined as:

$$f_{\mathrm{c}}(i) = 10^{i/10} \ , \qquad \text{(A-8)}$$

and the low (f_{lo}) and high (f_{hi}) frequency limits of the ith 1/3-octave band are defined as:

$$f_{\mathrm{lo}} = 10^{-1/20} f_{\mathrm{c}}(i) \quad \text{and} \quad f_{\mathrm{hi}} = 10^{1/20} f_{\mathrm{c}}(i) \qquad \text{(A-9)}$$

The 1/3-octave bands become wider with increasing frequency, and on a logarithmic scale the bands appear equally spaced (Figure A-2).

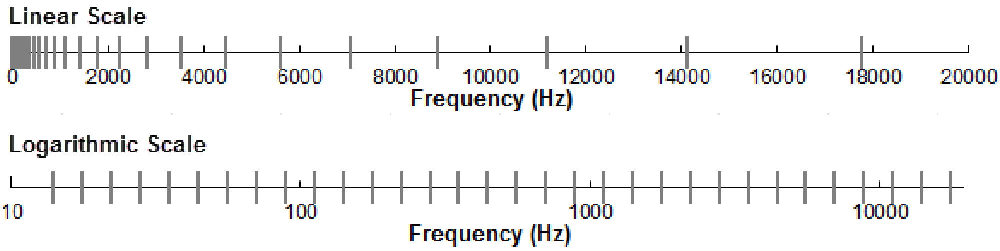

Figure A-2. One-third-octave-bands shown on a linear frequency scale and on a logarithmic scale.

The sound pressure level in the ith 1/3-octave band $(L_b^{(i)})$ is computed from the power spectrum $S(f)$ between f_{lo} and f_{hi}:

$$L_{\mathrm{b}}^{(i)} = 10\log_{10}\left(\int_{f_{lo}}^{f_{hi}} S(f)df\right) \tag{A-10}$$

Summing the sound pressure level of all the 1/3-octave bands yields the broadband sound pressure level:

$$\text{Broadband SPL} = 10\log_{10}\sum_i 10^{L_{\mathrm{b}}^{(i)}/10} \tag{A-11}$$

Figure A-3 shows an example of how the 1/3-octave band sound pressure levels compare to the power spectrum of an ambient noise signal. Because the 1/3-octave bands are wider with increasing frequency, the 1/3-octave band SPL is higher than the power spectrum, especially at higher frequencies.

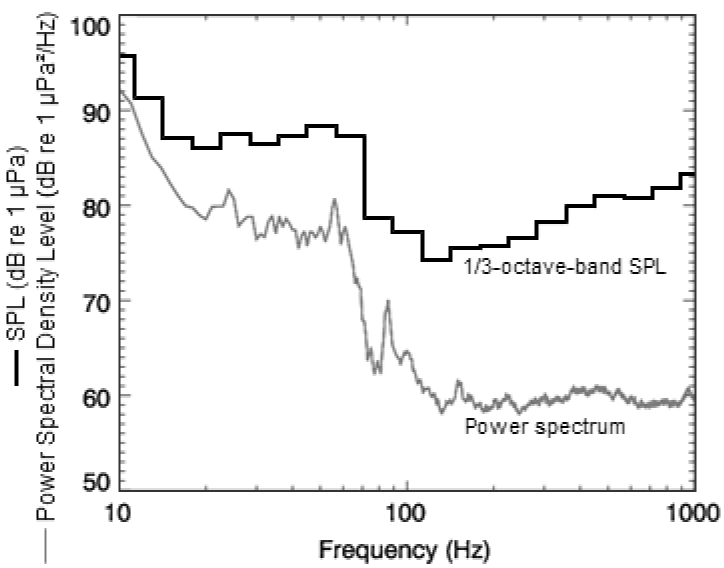

Figure A-3. A power spectrum and the corresponding 1/3-octave band SPLs of ambient noise shown on a logarithmic frequency scale. Because the 1/3-octave bands are wider with increasing frequency, the 1/3-octave band SPL is higher than the power spectrum.

A.3. Sound Level Statistics

Sound level statistics quantify the observed distribution of recorded sound levels. Following standard acoustical practice, the *n*th percentile level (L_n) is the spectral density, SPL or SEL exceeded by *n*% of the data. L_{max} is the maximum recorded sound level. L_{mean} is the linear arithmetic mean of the sound power, which can be significantly different from the median sound level (L_{50}). In this report, the median level is used to compare the most typical sound level between stations, since the median is not as affected by high outliers as the mean sound level. L_5, the level exceeded by only 5% of the data, generally represents the highest typical sound levels measured. Sound levels between L_5 and L_{max} are due to close passes of vessels, intense weather, or other abnormal conditions. L_{95} represents the quietest typical conditions.

The cumulative distribution function (CDF) provides another representation of the sound level statistics. The CDF of any measured quantity, such as the rms SPL, at any value is the probability that the data was at least that value. The x-axis of these figures is the measured quantity (rms SPL), while the y-axis is the percentage of the measurements that exceeded the x-axis value.

Appendix B. Automated Detector Processes

B.1. Total Ocean Noise And Time Series Analysis

The total ocean noise levels were quantified at a 1 Hz frequency resolution and were averaged to produce sound pressure density values for each 1 Hz step of the recorded bandwidth over each minute of recording. Further analyses yielded 1/3-octave band levels, which corresponds approximately with the hearing filter bandwidth in terrestrial mammals, and decade band, a logarithmic filter bandwidth, sound pressure levels for each minute of data.

B.2. Vessel detections

Vessel detection was performed in two steps. In the first step, narrowband sinusoidal tones (tonals) produced by the ship's propulsion and other rotating machinery (Arveson and Vendittis 2000) were detected in each file of the 64 ksps data. The tonal detector is based on overlapping FFTs. The number of seconds of data input to the FFT determines its spectral resolution. Arveson and Vendittis (2000) used 0.5 and 0.125 Hz resolutions. For this study, spectral analysis was performed at 0.125 Hz resolution by using 8 s of real data with a 2 s advance. By using this frequency resolution, the tones could be separated from each other for easy detection; the 2 s advance provides suitable temporal resolution. Higher frequency resolutions can reduce detectability of shipping tones, which are often unstable within 1/16 Hz for long periods. Thus, we created a 120 s long spectrogram with 0.125 Hz frequency resolution and 2 s time resolution (32768-point FFTs, 32000 real data points, 16000-point advance, Hamming window). A split-window normalizer (Struzinski and Lowe 1984) distinguished the tonal peaks from the background (2 Hz window, 0.75 Hz notch, and detection threshold of 4 times the median). The peaks were joined with a 3 × 3 kernel to create contours. Associations in frequency are made if contours occur at the same time. We recorded the event time and number of tones for any event that lasted at least 20 s and 40 Hz in bandwidth for further analysis.

In the second step, the results from all the files were combined to detect ship passages. A "shipping band" is defined at 40–315 Hz and rms SPL for the band was obtained once per minute. Background estimates of the shipping band rms SPL and the total rms SPL were compared to their median values over the 12 h window, centered on the current time. We deemed shipping to have been detected when the rms SPL in the shipping band was at least 3 dB above the median, when at least 5 shipping tonals are present, and when the rms SPL in the shipping band is within 8 dB of the total rms SPL in the evaluation window (Figure B-1).

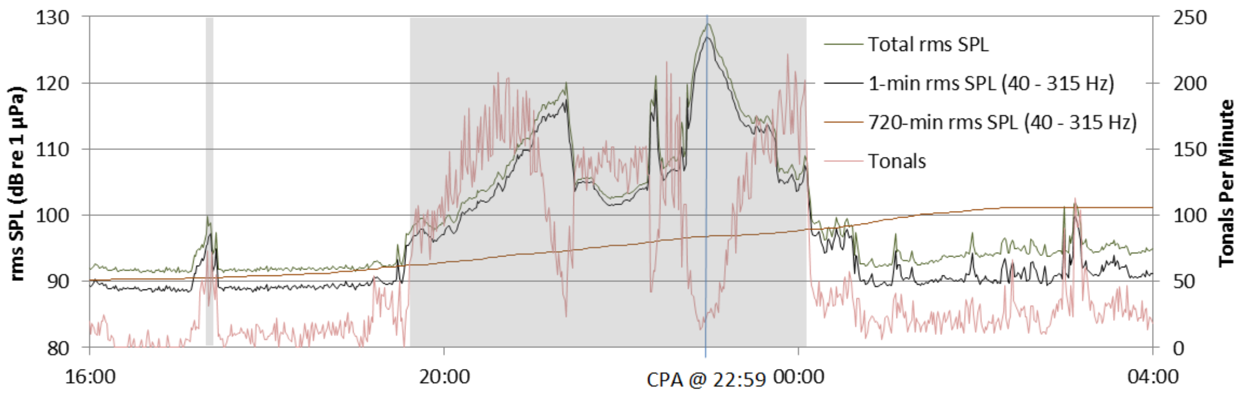

Figure B-1. Example of broadband and in-band rms SPL and the number of 0.125 Hz wide tonals detected per minute as a ship approached a recorder, stopped, and then departed. The shaded area is the period of shipping detection. All tonals are from the same vessel. Fewer tonals are detected at the ship's closest points of approach (CPA) at 22:59 because of the broadband cavitation noise at CPA and the Doppler shift of the tonals.

B.3. Bowhead, Gray whale, beluga, walrus, and bearded seal call detections

An automated detector was used to detect walrus, bearded seal, gray whale,bowhead and beluga whale vocalizations from acoustic recordings. Figure B-2 shows the detector's various processing steps.

The algorithm first calculated the spectrogram and normalized it for each frequency band. Then the spectrogram was segmented between 10 and 4000 Hz to define acoustic events in the spectrogram. For each event, a set of features representing salient characteristics of the spectrogram were extracted. Extracted features were presented to a five-class random forest classifier to determine the class of the sound detected (i.e., "bowhead", "Gray whale", "beluga", "walrus", "bearded seal", or "noise"). During the training phase, features of known sounds (i.e., manual annotations) were extracted to create the random forest model. Figure B-3 illustrates the detection process.

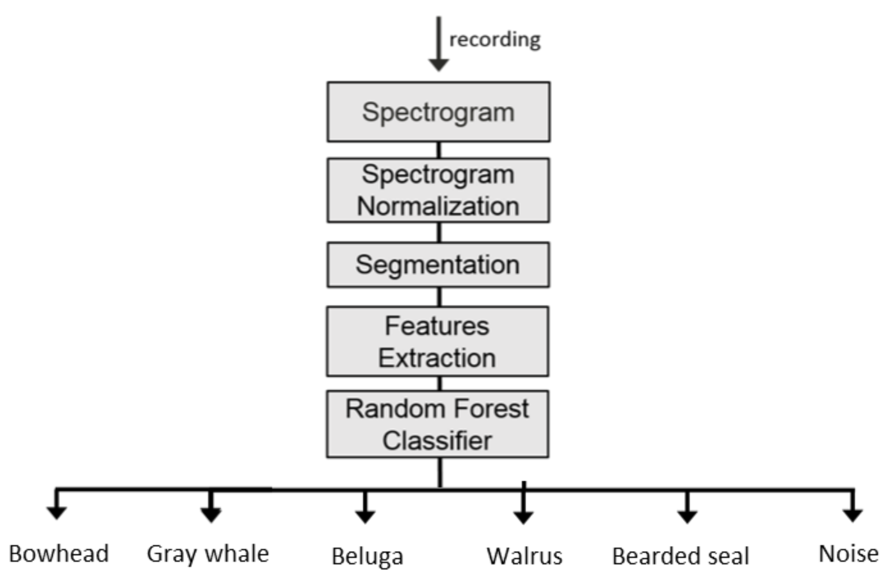

Figure B-2. The detector's automated processing.

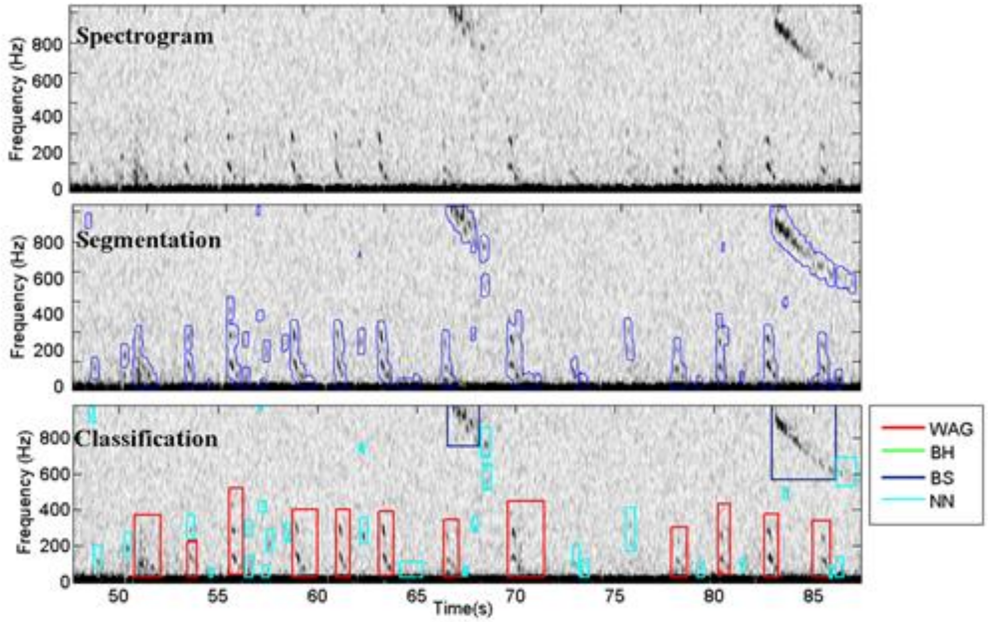

Figure B-3. Example data showing the steps of the automated detector. Blue lines in the middle panel indicate edges of detected objects. Colors in the bottom panel indicate whether objects were classified as walrus (WAG, red), bowhead (BH, green), bearded seal (BS, dark blue), or noise (NN, light blue).

Step 1-2: Spectrogram Processing

The spectrogram resolution was chosen to ensure accurate time-frequency representation of all vocalization of interest (Table B-1). The spectrogram was normalized by a split window normalizer using a window of 4 s and a notch of 2 s (Struzinski and Lowe 1984).

Table B-1. Spectrogram parameters used in the detector.

Analysis frame size (s)	0.1
Increment between frames (s)	0.02
FFT size (sample)	0.1
Window function	Blackman

Step 3: Spectrogram segmentation

The spectrogram is segmented by calculating the local variance of energy values on a 2-dimensional kernel. The local variance was calculated twice using different sizes of kernel. The first pass was performed using a kernel of 0.1 s by 100 Hz. Areas of the spectrogram with a local variance less than 0.6 were set to zero (variance units: energy^2). The second pass used a kernel of size 0.2 s by 300 Hz. Areas of the spectrogram with a local variance less than 0.4 were set to zero (variance units: energy^2). The first pass defined each component of the transients at small scale, while the second pass removed small noise objects and group together calls with harmonics. Edges of the remaining area of the spectrogram were defined using the Moore Neighborhood algorithm (Ainslie and McColm 1998). Figure B-3 (middle panel) shows an example of the segmentation process. Finally, only objects longer than 100 ms and larger than 50 Hz were kept for classification.

Step 4: Feature Extraction

Features for each object were extracted on a time-frequency box that contains 95% of the energy of the initial object (red box in Figure B-4; top panel). Each object was represented by 40 features, several of which were calculated following Fristrup and Watkins (1993) and Mellinger and Bradbury (2007), using the spectrogram, frequency envelope, and amplitude envelope of the signal (Figure B-4). The frequency envelope is the sum of the spectrogram amplitudes for each frequency. The maximum of the frequency envelope was normalized to 1. The amplitude envelope is the sum of the spectrogram amplitude values for each time step. The frequency and amplitude envelopes were interpolated to have a resolution of 1 Hz and 1 ms respectively. Features include the following:

- Median frequency, f_{med}: Based on the frequency envelope. The cumulative sum of the spectrum was calculated by moving from low to high frequencies. The median frequency is the frequency at which the cumulative energy reaches 50% of the total energy (green dashed line in Figure B-4).
- Spectral inter-quartile range: Calculated by defining the 25th percentile of the energy on each side of the median frequency (dashed blue lines in Figure B-4). Each quartile was defined as frequency for which the cumulative energy calculated from the median frequency equaled 25% of the total energy. The spectral inter-quartile range is the difference between the higher (f_{Q3}) and lower quartiles (f_{Q1}).
- Spectral asymmetry: Skewness of the spectral envelope calculated as $(f_{Q1} + f_{Q3} – 2f_{med})/(f_{Q1} + f_{Q3})$.
- Spectral concentration: Calculated by ranking amplitude values of the spectral envelope from largest to smallest. The cumulative sum of ranked amplitude values was computed beginning with larger values until 50% of the total energy was reached. The lowest frequency index included in the additive set was considered the minimum; the highest index was the maximum, with their difference providing the spectral concentration (red box in Figure B-4).
- Maximum frequency peak: Frequency of the highest amplitude peak in the spectral envelope (red dot in Figure B-4).
- Maximum frequency peak width: Width (Hz) of the maximum frequency peak measured at the point where amplitude values on each side of the peak reached the 75th percentile of all the spectral envelope amplitude values (red vertical line in Figure B-4)
- Difference in Hz between the maximum frequency peak and the median frequency of the frequency envelope.
- Maximum and minimum frequency of the object.
- Frequency bandwidth and duration of the object.
- Variance and kurtosis of frequency envelope: These describe the distribution of the amplitude in the spectral envelope (Balanda and MacGillivray 1988).
- Frequency modulation index was calculated as follows:
  - First, the maximum frequency of the maximum amplitude peak was extracted for each time slice of the spectrogram. Frequency values of the selected peaks were stored in the vector F_{max}, and their associated energy values in the vector E_{max}. Only peaks with an amplitude value exceeding the median amplitude of the spectrogram were considered (white dots in Figure B-4b).
  - Second, the weighted maximum frequency offset vector O was defined as $O = (F_{max} – X_{med}) \cdot E_{max}/max(E_{max})$, where X_{med} is a scalar representing the median frequency of the vector F_{max}. The frequency modulation index was defined as the standard deviation of the vector O.
- Frequency and correlation value of the maximum peak in the autocorrelation function calculated on the frequency envelope.
- Temporal inter-quartile range: same as the frequency inter-quartile range but calculated on the time envelope.
- Temporal asymmetry: same as the frequency asymmetry but calculated on the time envelope.
- Temporal concentration: same as the frequency envelope but calculated on the time envelope.
- Variance and kurtosis of the time envelope.

- Period and correlation value of the maximum peak in the autocorrelation function calculated on the time envelope.
- Several features based on the contour representing the evolution in time of the median frequency. These include the number of inflection points, upsweep and downsweep rates, standard deviation, and variance of frequency values.

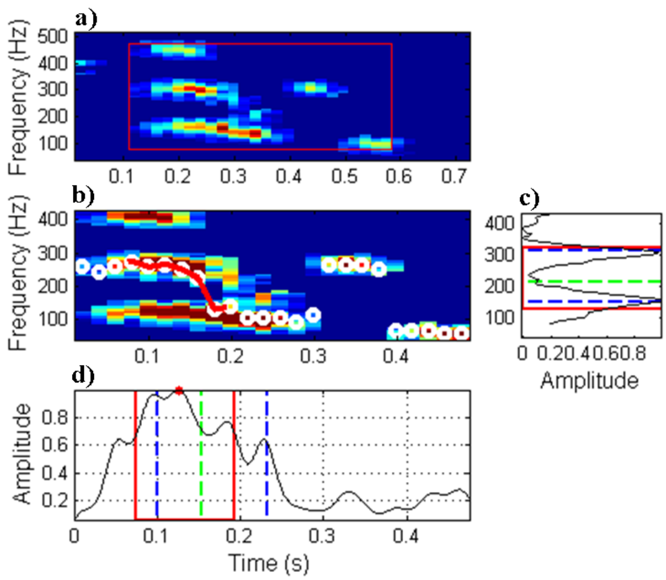

Figure B-4. Extraction of features used in the classifier: (a) Spectrogram of the original object detected. The red rectangle indicates the zone including 95% of the energy. (b) Spectrogram of the resized object including 95% of the energy. White dots indicate the median at each time step and the red line indicates the median contour; (c) frequency envelope (black line), with the median frequency (green line), the upper and lower quartiles (blue lines), and the spectral concentration (red box); (d) amplitude envelope with the median (green line), the upper and lower quartiles (blue lines), and the temporal concentration (red box).

Step 5: Classification

Classification was performed using a random forest classifier (Breiman 2001), which was trained using all manual annotations in recordings from thousands of manually annotated vocalizations recorded in the Arctic (Mouy et al. 2013). The random forest was defined with these five classes: “bowhead”, “beluga”, “walrus”, “bearded seal”, and “noise”.

B.3.1. Tonal Call Detector

Marine mammal tonal calls (e.g., bearded seal calls, beluga whistles) were detected using a tonal detector searching for energy in defined frequency bands. Low-frequency moans were calls under 200 Hz, mid-frequency moans were detected between 200 and 1000 Hz, and whistles were defined as tonal calls above 1000 Hz.

Table B-2 lists the spectrogram parameters used in the first step of the tonal call detection process. To attenuate long spectral rays in the spectrogram due to vessel noise, and to enhance weaker transient biological sounds, the spectrogram was normalized in each frequency band (i.e., each row of the spectrogram) with a median normalizer whose duration is set by the Detection Window duration (Table B-2). The normalized spectrogram was binarized by setting to 1 all the time-frequency bins that exceed a normalized amplitude of 3 (Detection Threshold, Table B-2, no units); the other bins were set to 0.

Table B-2. FFT and detection window settings for marine mammal call detection used. Values are based on JASCO's experience and empirical evaluation on a variety of data sets.

Call type	Species	FFT resolution (Hz)	FFT data duration (s)	FFT data advance (s)	Detection window (s)	Detection threshold
High whistle	Beluga	64	0.015	0.005	30	3
Low whistle	Beluga	32	0.03	0.01	30	3
High moan	Seals	2	0.25	0.125	120	3
Low moan	Seals	2	0.25	0.125	120	3

The second step of the detection process consisted of defining time-frequency objects (or events) by associating contiguous bins in the binary spectrogram. The algorithm implemented is a variation of the flood-fill algorithm (Nosal 2008). Every spectrogram bin that equals 1 and is separated by one FFT bin in either time or frequency are connected (Figure B-5). The bin connection process moves from oldest data to newest and from lowest frequency to highest. Each group of connected bins is referred to as a time-frequency object. A spectrogram bin can only belong to one time-frequency object. A call sorting algorithm determines if the contours match the definition of a mammal call type (Table B-3). Recorded data with a significant number of detections of any call type were reviewed manually to check for mammal presence and ensure species were accurately classified.

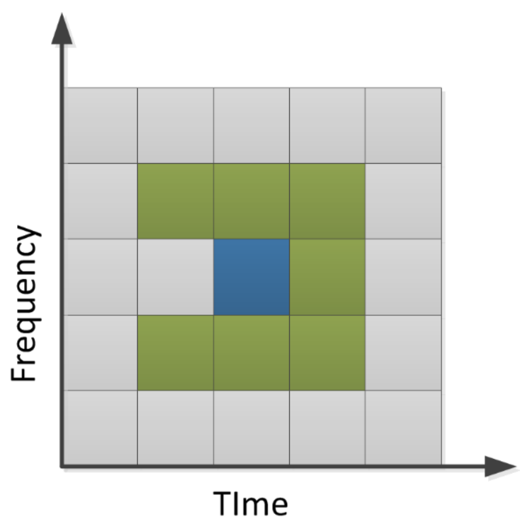

Figure B-5. Illustration of the search area used to connect spectrogram bins. The blue square represents a bin of the binary spectrogram that equals 1; the green squares represent the potential bins to which it could be connected. The algorithm advances from left to right so gray cells left of the test cell need not be checked.

Table B-3. Call sorter definitions for the detection of mammal calls. Contour sound pressure level (SPL) must be higher than period before and after contour.

Call type	Frequency	Duration (s)	Bandwidth (Hz)	Maximum bandwidth per time cell (Hz)	Sweep rate (Hz/s)
High whistle	5–20 kHz	0.15–2.0	> 700	2500	Any
Low whistle	0.5–10 kHz	0.3–2.0	> 500	700	Any
High moan	200–2000 Hz	0.65–5	> 40	50	Any
Low moan	50-400 Hz	0.5–6	> 20	30	Any
Bearded seal downsweep	200-1500	1-10	> 100	120	−500–30
Bearded seal upsweep	150-2000	1-6	> 100	120	100–1000

B.3.2. Automated Click Detectors

An automated click detector/classifier based on the zero crossings in the acoustic time series was used to detect clicks.

The click detector/classifier (Figure B-6) progresses through these stages:

1. The raw data was high-pass filtered, which removed all energy below 8 kHz. This filter removes most energy from other sources—for example, vessels, wind, shrimp, and cetacean tonal calls—yet allows the energy from all marine mammal click types to pass.
2. The filtered samples were summed to create a 0.5 ms root-mean-square time series. Most marine mammal clicks have a duration of 0.1–1 ms.
3. A Teager-Kaiser energy detector (Kaiser 1990) identified possible click events.
4. The high pass filtered data was searched to find the maximum peak signal within 1 ms of the detected peak after which the filtered data was searched backwards and forwards to find the time span where the local data maxima are within 12 dB of the maximum peak. The algorithm allows for two zero crossings to occur where the local peak is not within 12 dB of the maximum before stopping the search; this defines the time window of the detected click.
5. The classification parameters were then extracted by computing the number of zero crossings within the click, the median time separation between zero crossings, and the slope of the change in time separation between zero crossings.
6. The Mahalanobis distance between the extracted classification parameters and the templates of known click types was computed. The covariance matrices for the known click types were computed based on thousands of manually identified clicks for each species. Each click was classified based on the minimum Mahalanobis distance, except when none met the specified distance threshold.

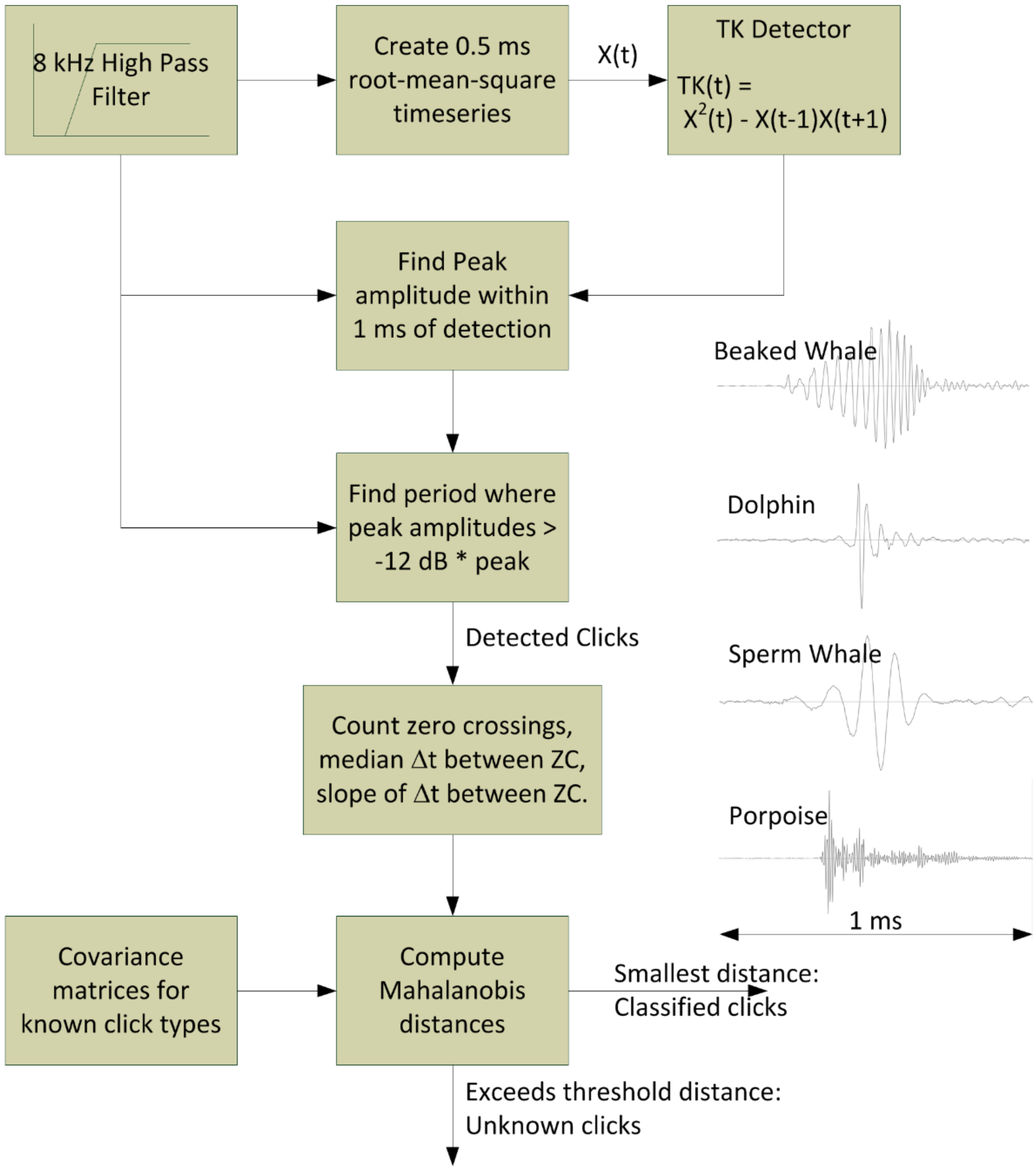

Figure B-6. Block diagram of the click detector/classifier. A 1 ms time series of four different click types is shown on the right.